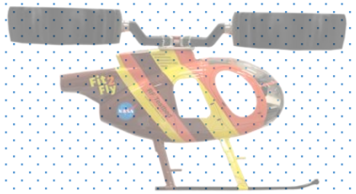

High-Intensity Radiated Field (HIRF) Map -

An Avoidance Approach for UAM, AAM, and UAS Vehicles

Truong Nguyen, NASA Langley Research Center

2023 Digital Avionics Systems Conference

October 1-5, 2023

Digital Avionics Systems Conference

Barcelona, Spain - October 1-5, 2023

Work Sponsored by NASA

System-Wide Safety (SWS) Project

Electrified Powertrain Flight Demonstration Project

Sponsors

- **System-Wide Safety Project**
  - Part of the Airspace Operations and Safety Program (AOSP) within the NASA Aeronautics Research Mission Directorate (ARMD).
  - **Goals**:
    - **Explore, discover, and understand how safety could be affected by the growing complexity of advanced aviation systems**.
    - Develop and demonstrate the research tools, innovative technologies, and operational methods that will **proactively mitigate potential risks** to maintain the aviation industry’s unparalleled safety record.

- **Electrified Powertrain Flight Demonstration Project**
  - Part of the Integrated Aviation Systems Program (IASP) within ARMD
  - **Goals**:
    - Conducts **ground and flight tests of electrified aircraft propulsion (EAP) technologies** to enable a new generation of electric-powered aircraft
    - NASA seeks to **introduce EAP systems to the U.S. commercial fleet** by conducting at least two flight demonstrations

Background

UAM: Urban Air Mobility
AAM: Advanced Air Mobility
UAS: Unmanned Aircraft Systems

- Aircraft, rotorcraft, and other air vehicles may be exposed to very **high EM field environments (HIRF)**
  - HIRF Susceptibilities **could lead to catastrophic events**
  - Digital upset, equipment reset, damage to hardware/ICs, loss of communication/data, analog measurement errors…
- Existing HIRF standards are **based on the worst-case environments** worldwide
- **Rotorcraft environment worse than aircraft**
  - Operates close to ground transmitters
  - Can hover in front of transmitters
  - Resulting in very severe HIRF test levels
- **UAM/AAM/UAS vehicles may operate similarly to rotorcraft**
  - Require testing to the same HIRF levels as for rotorcraft
  - Vehicles often lack metal skin for shielding
- **HIRF protection cost, size, weight, and power concerns for UAM/AAM/UAS vehicles**

Goal: Develop a suitable approach to reduce costs associated with HIRF Protection and Certification

Aircraft and Rotorcraft HIRF Environments

- **14 CFR 27—AIRWORTHINESS STANDARDS**

TABLE 3 - Certification HIRF Environment (HIRF Environment I)

FREQUENCY	FIELD STRENGTH (V/M)	
	PEAK	AVERAGE
10 kHz - 100 kHz	50	50
100 kHz - 500 kHz	50	50
500 kHz - 2 MHz	50	50
2 MHz - 30 MHz	100	100
30 MHz - 70 MHz	50	50
70 MHz - 100 MHz	50	50
100 MHz - 200 MHz	100	100
200 MHz - 400 MHz	100	100
400 MHz - 700 MHz	700	50
700 MHz - 1 GHz	700	100
1 GHz - 2 GHz	2000	200
2 GHz - 4 GHz	3000	200
4 GHz - 6 GHz	3000	200
6 GHz - 8 GHz	1000	200
8 GHz - 12 GHz	3000	300
12 GHz - 18 GHz	2000	200
18 GHz - 40 GHz	600	200

TABLE 2 - ROTORCRAFT SEVERE HIRF ENVIRONMENT (HIRF ENVIRONMENT III)

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz - 100 kHz(1)	150	150
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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

Proposed Solution & Approach

Solution: Provide a **map of HIRF avoidance zones**, tailored for each AAM vehicle

(A) **Transmitter Power**	-	(B) **Propagation Loss** (HIRF Map)	<	(C) **Vehicle Tolerance**

(A) Fixed-transmitter databases

(B) "HIRF Map" to be used in **flight-path planning**

(C) Vehicle's HIRF tolerant level

- User defined
- Higher tolerance ➔ Smaller HIRF zone

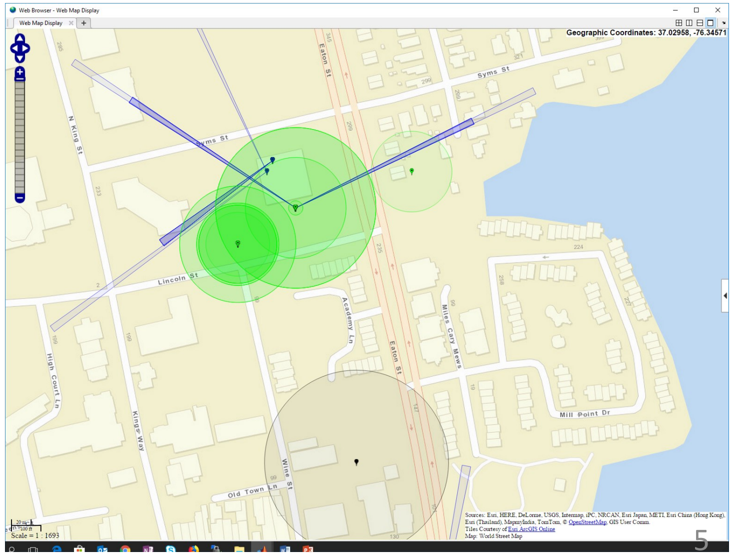
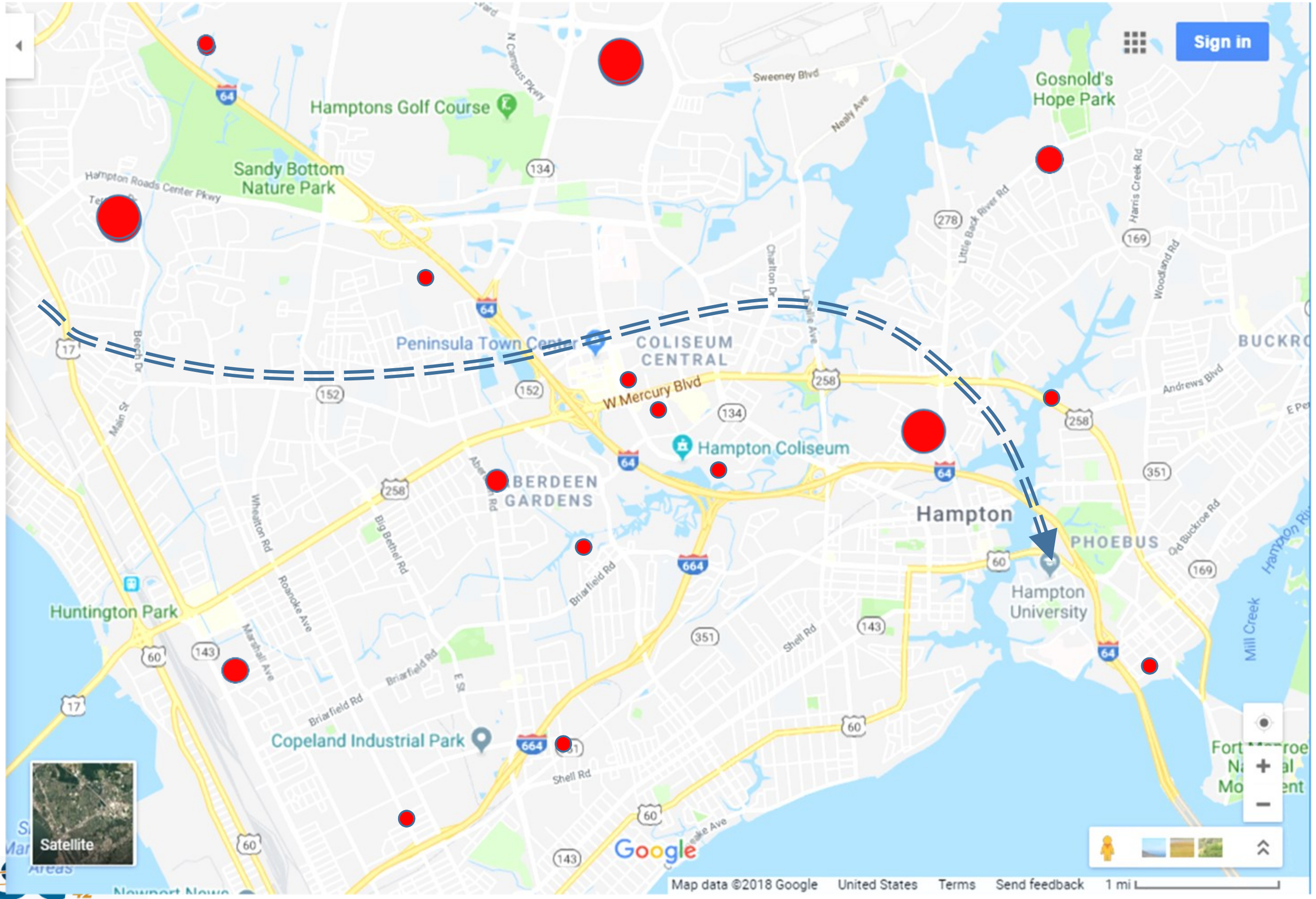


Illustration of Flight Planning

"Keep-out" zones, with field strength potentially exceeds the UAV's tolerant levels



- HIRF Sources may include:
  - AM, FM, TV antennas
  - Satellite comm. antenna
  - Cell-tower antennas
  - Commercial radios
  - Land Mobile radios
  - Maritime Coast
  - Aviation
  - Radar (weather,…)
  - Airport transmitters
  - …

Illustration only. Not actual transmitters

Benefits

- **Advantages**
  - Avoid designing/certifying to the globally-defined worst-case HIRF environment
  - Faster and cheaper to design, build, test, and certify
    - Whole-vehicle HIRF testing in test chambers

- **Disadvantages**
  - Slightly more complex flight planning
  - Transmitters databases unique to individual countries
  - Uncertainties in the transmitter databases
    - Unknown transmitters (i.e. military sites)

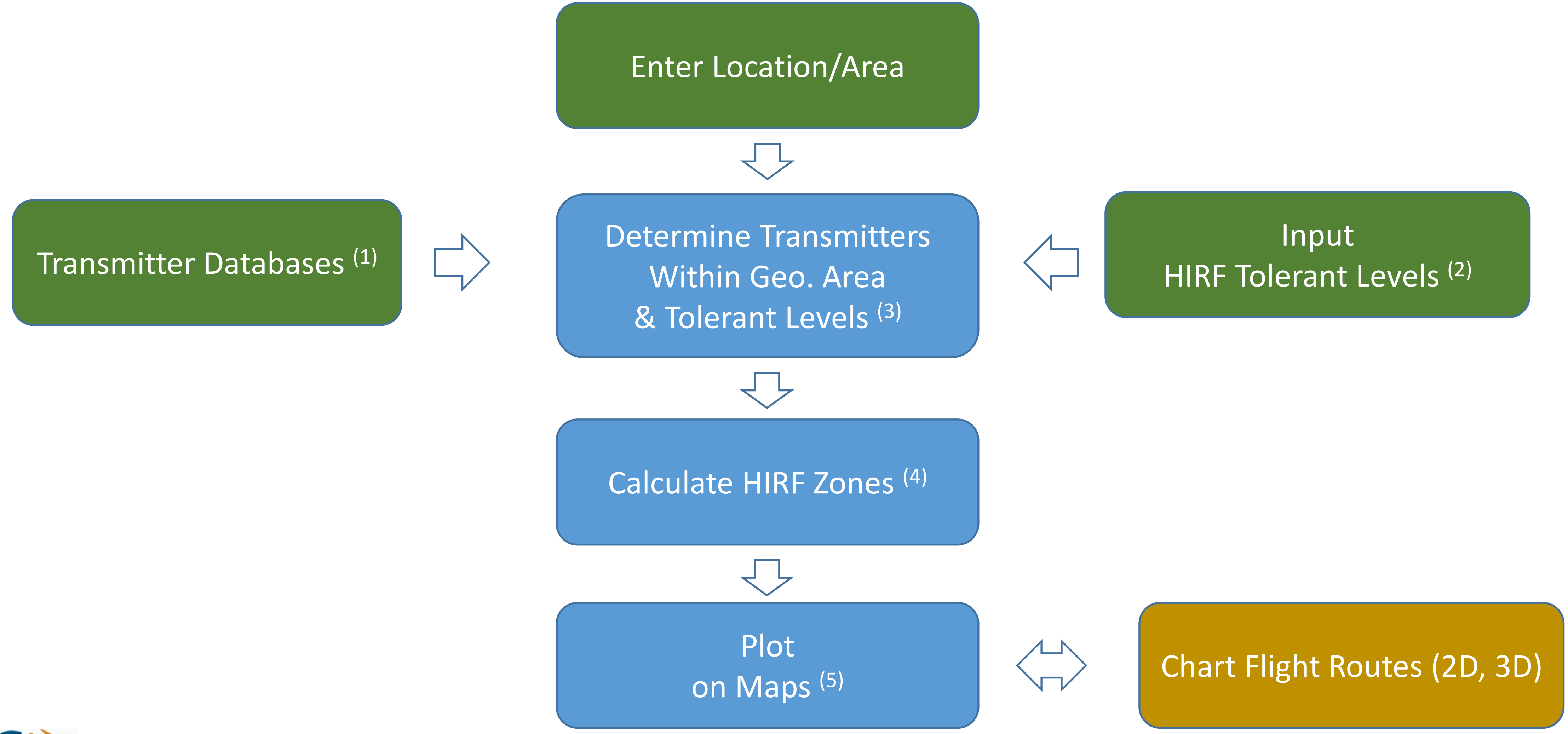
Proof-of-Concept

<u>Proof-of-Concept:</u> To develop a HIRF-Map tool, and to identify key issues

The HIRF-Map Tool is developed in Matlab

- **Import Databases** (FCC, NOAA,…)
    - Limit transmitters to those within geographical zone
- **Calculate the HIRF zone** for each transmitter/carrier
    - From <u>user-defined HIRF tolerant levels</u>
    - Use worst-case power and gain data
- **Overlay** HIRF zones **on WebMap**
- **Add flight paths**

Implementation



(1) Fixed Transmitter Databases in the U.S.

Databases Incorporated

- **FCC** (Federal Communications Commission)
- **NOAA weather radars**

  (National Oceanic and Atmospheric Administration)

Other Databases

NTIA Databases

(National Telecommunications and Information Administration)

- Transmitters operating in spectrum reserved for federal use
- GMF → EL-CID
- Not publicly accessible

FAA (Federal Aviation Administration)

- Info on Airport radars & others
  - Air Route Surveillance Radar
  - Airport Surveillance Radar
- Not publicly accessible

FCC License Databases

- **CDBS** Consolidated Database System
  - AM, FM, TV stations licenses
- **IBFS** International Bureau Filing System
  - Satellite Earth Stations (SES), Satellite Space Stations
- **ULS** Universal Licensing System
  - A collection of databases of less powerful transmitters

ULS - Fixed Transmitters

- **Cellular**
  - FCC Database Incomplete!
  - Private Data by mobile carriers: Proprietary, incomplete
  - Crowd-based data (inaccurate)(i.e., OpenSignal, CellMapper)
- **Market Based**
- **Microwave** Link
- **Land Mobile -**
  - Commercial
  - Private
  - Broadcast
- **MDS / ITFS**
  - Multipoint Distribution Service (MDS)
  - Instructional Television Fixed Service (ITFS)
- **Marine Coastal and Aviation Ground**
- **Paging**

NOAA Weather Radars

TDWR (Terminal Doppler Weather Radar)

NEXRAD (Next Generation Weather Radar)

	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

➔ Effective Isotropic Radiated Power (**EIRP**) = **~ 25 – 27 billion watts (peak)**

(2) HIRF Tolerant Level

- **User defined and verified through testing/analysis**
- Levels should be much lower than existing requirements
  - Unique to vehicle
- Level may vary with frequency
- Should be grouped and enveloped into bands segments, similar to table ->
- Modulations simplified to CW, AM, and Pulse to match standards

TABLE 2 - ROTORCRAFT SEVERE HIRF ENVIRONMENT (HIRF ENVIRONMENT III)

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

Note: In later discussions, uniform field tolerant levels across all frequency segments are assumed for discussion simplicity

(3) Transmitter Data Mapping & Usage

Transmitter Data	Used for
Frequency	Map to one of Frequency Bands
Modulation Types (AM, FM, phase, pulse-width/position, single-side bands with full/suppress carrier, vestigial sideband,…)	Map to CW, AM, Pulse
Power, Gain	Calculating HIRF zone radius
GPS Location	Plot on Map
Transmitter Type & details	Marker, colors, Pop-ups
Angular Range, Beam Elevation	Plot on Map (circular or angular sector)
Antenna height	Future 3D mapping

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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
[illegible]	5000	330
12 GHz - 18 GHz	2000	330
18 GHz - 40 GHz	1000	420

$$R = \frac{1}{E}\sqrt{30PG}$$

(4) Calculate HIRF Zones

$$E = \frac{1}{R}\sqrt{30PG}$$

$$\boxed{R = \frac{1}{E}\sqrt{30PG}}$$

E = E-field tolerance level
R = Stand-off distance
P = Radiated Power
G = Antenna Gain
EIRP = PG = Eff. Isotropic Radiated Power

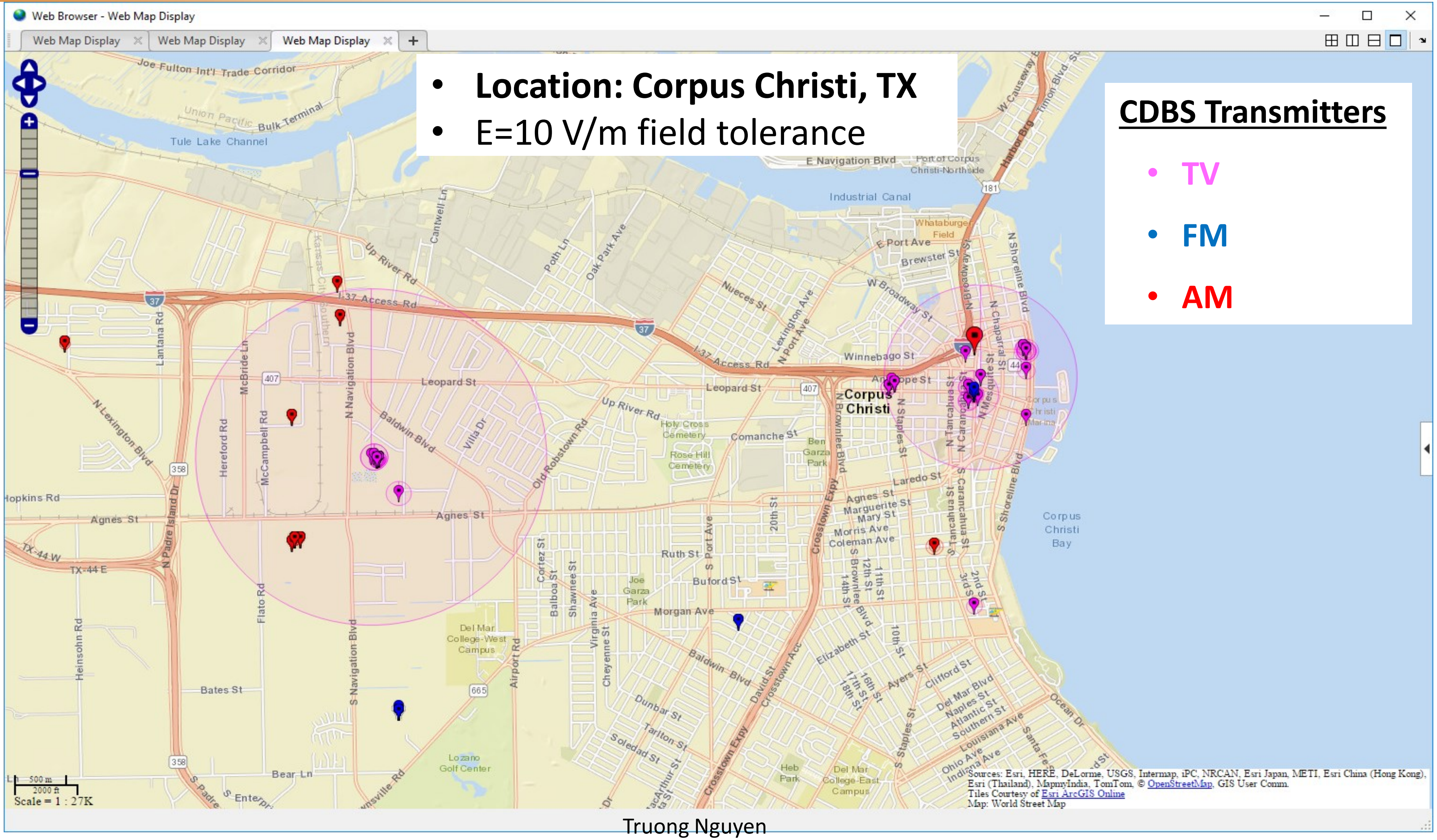
- The worst-case data is assumed, to be conservative
  - Ignore antenna pattern
- **The HIRF zone is a circular region with a radius R**
  - Angular range is incorporated if known
  - R is scaled for elevation angle if known

(5) Plot HIRF Map

- **Used Webmap Tools in Matlab**
- **Ignore cumulative effects** from multiple carriers (similar to existing HIRF standards)
- **Ignore high-order effects** (ground bounce, multi-paths, diffractions)
- Display **HIRF zones for each carrier**
  - Darker shades → higher number of carriers
  - **Circular zones** for most transmitters
  - **Angular sectors** for microwave and satellite base station if data is available
- Also includes additional map info:
  - Airport and helipad locations
  - Military base boundaries

CDBS Database Example

- **Location: Corpus Christi, TX**
- E=10 V/m field tolerance

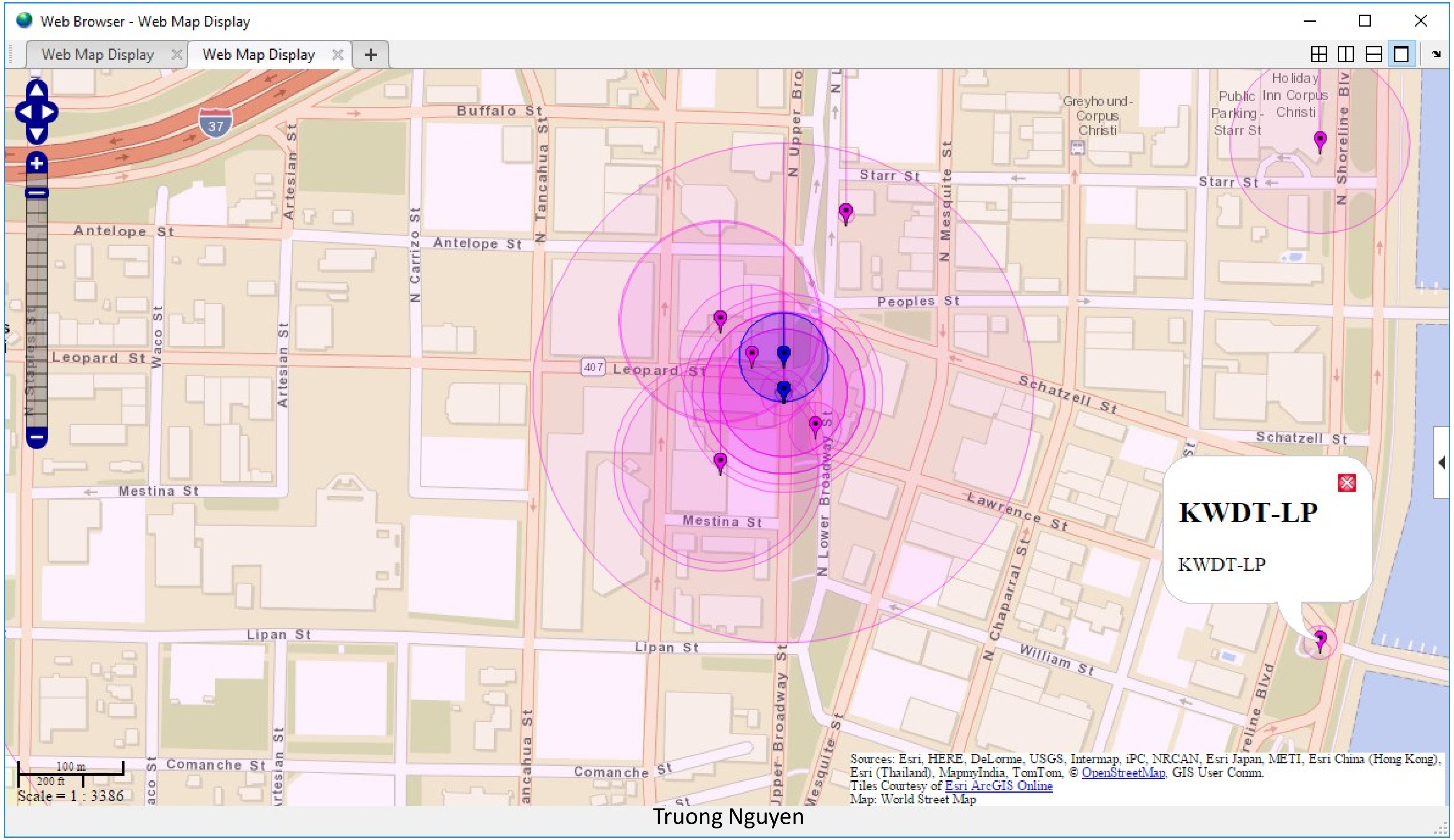


CDBS Transmitters

- TV
- FM
- AM

CDBS Database Example

- HIRF zones for TV and FM Radio stations
- Multiple carriers



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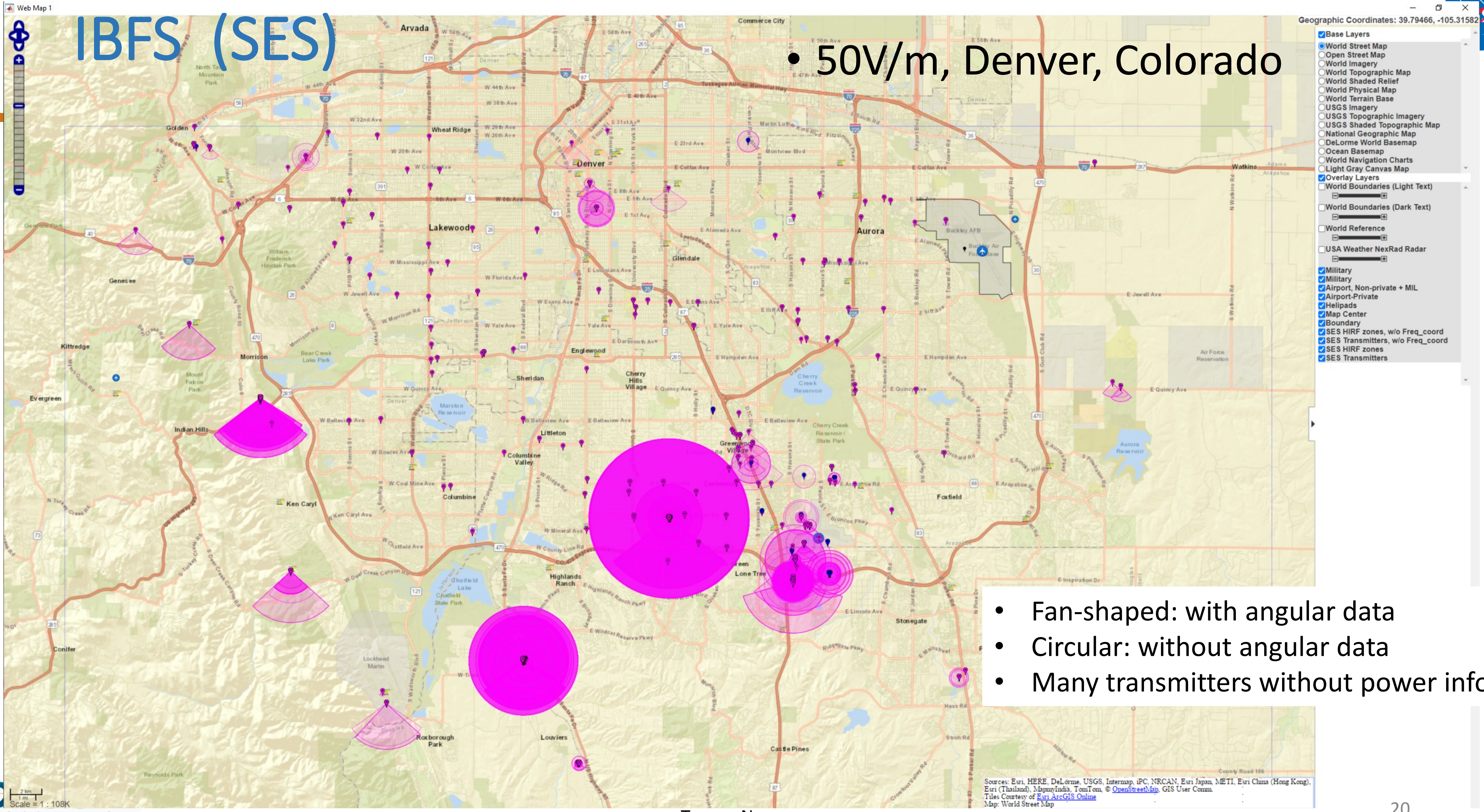
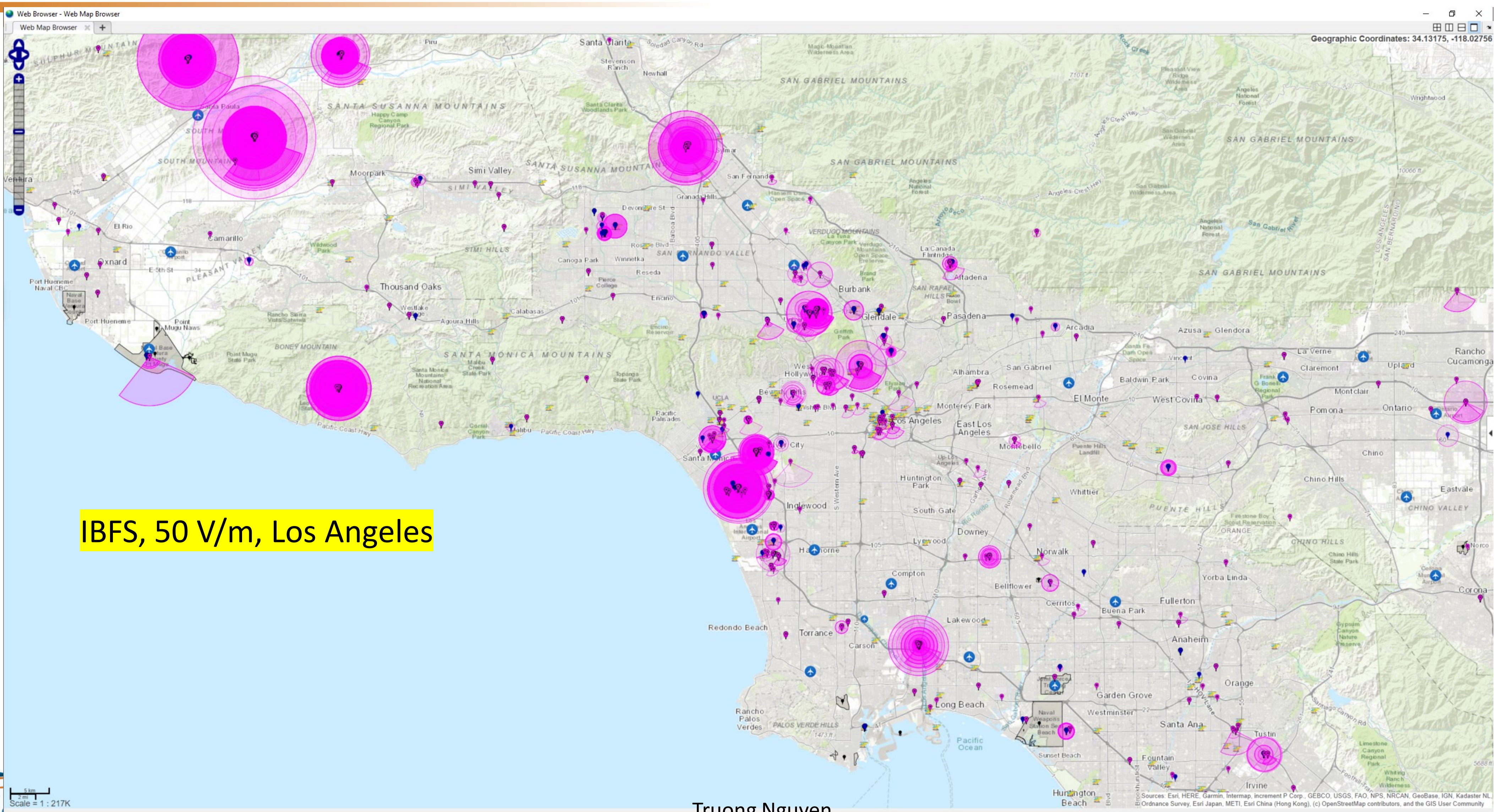
IBFS (SES)

- 50V/m, Denver, Colorado

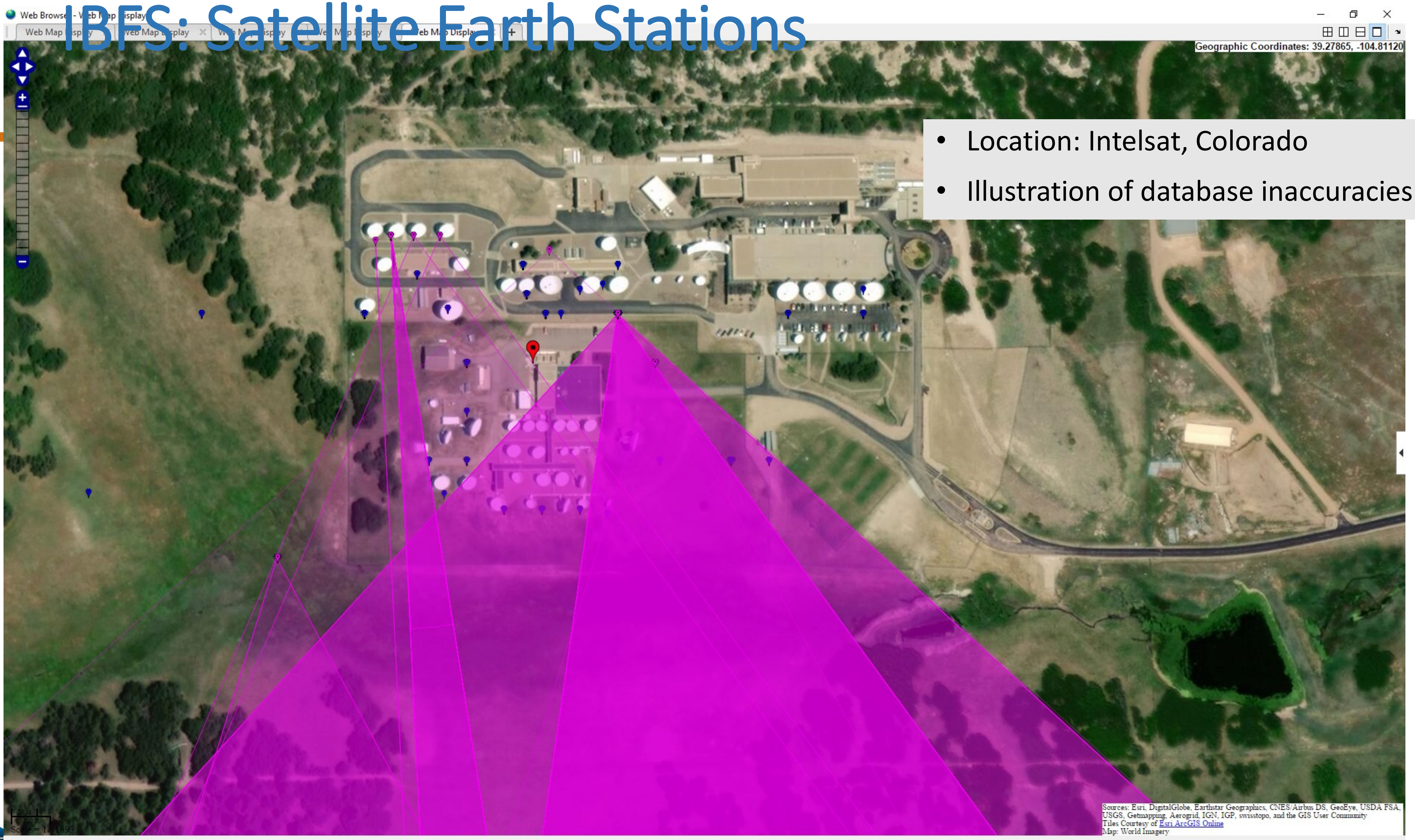


- Fan-shaped: with angular data
- Circular: without angular data
- Many transmitters without power info

IBFS, 50 V/m, Los Angeles Areas



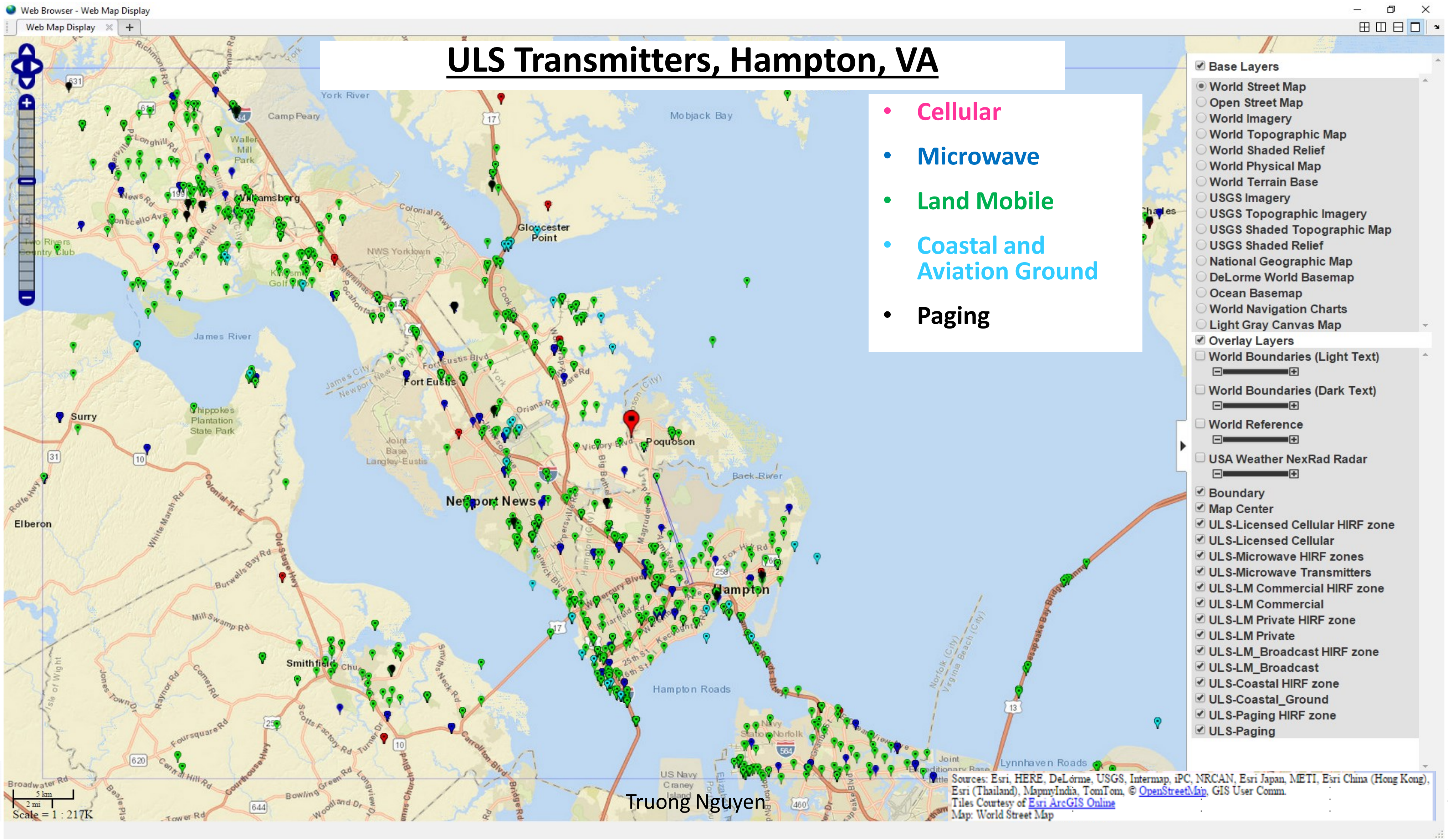
IBFS: Satellite Earth Stations



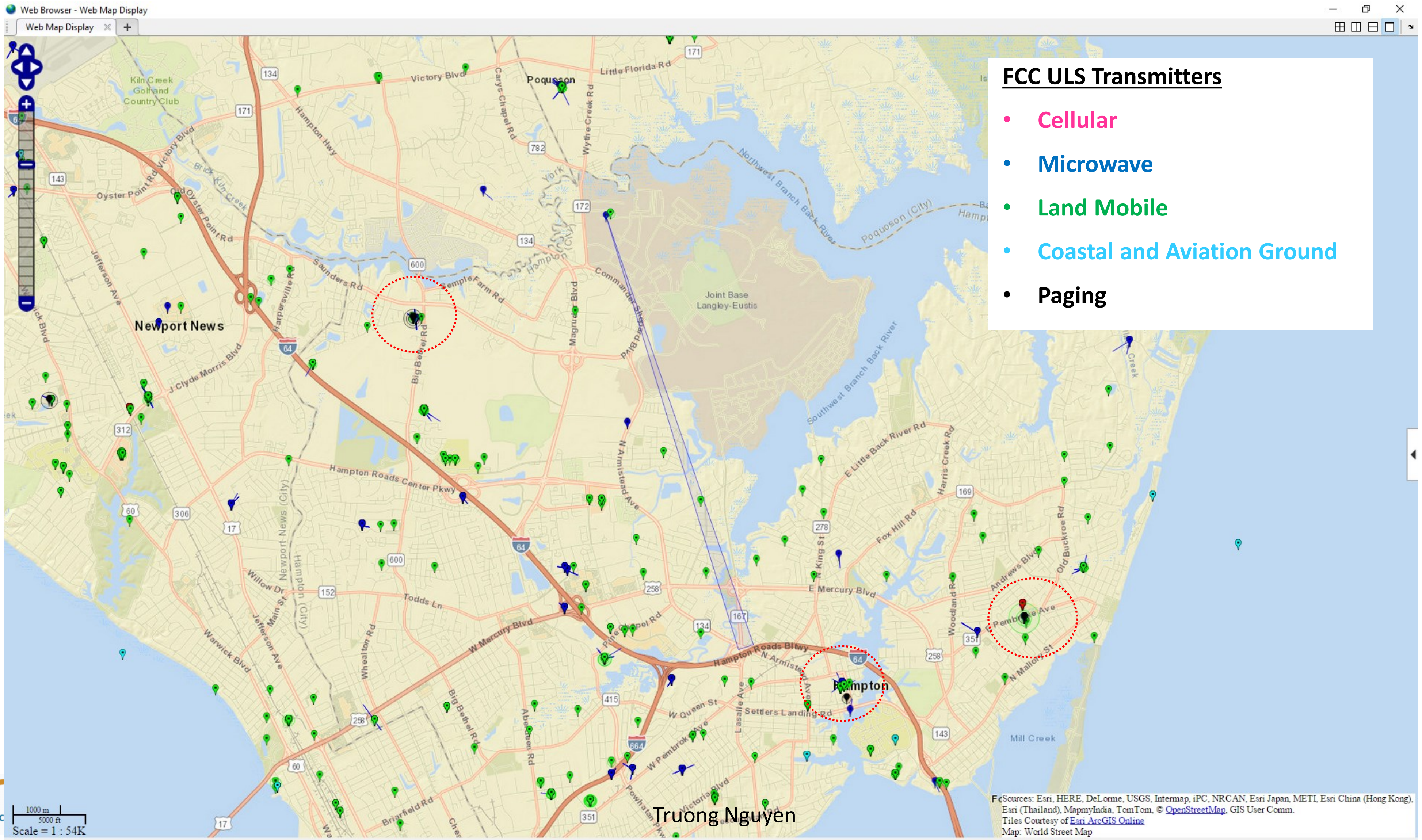
- Location: Intelsat, Colorado
- Illustration of database inaccuracies

ULS Database Example

Note: Lack of Cellular data



ULS Database Example



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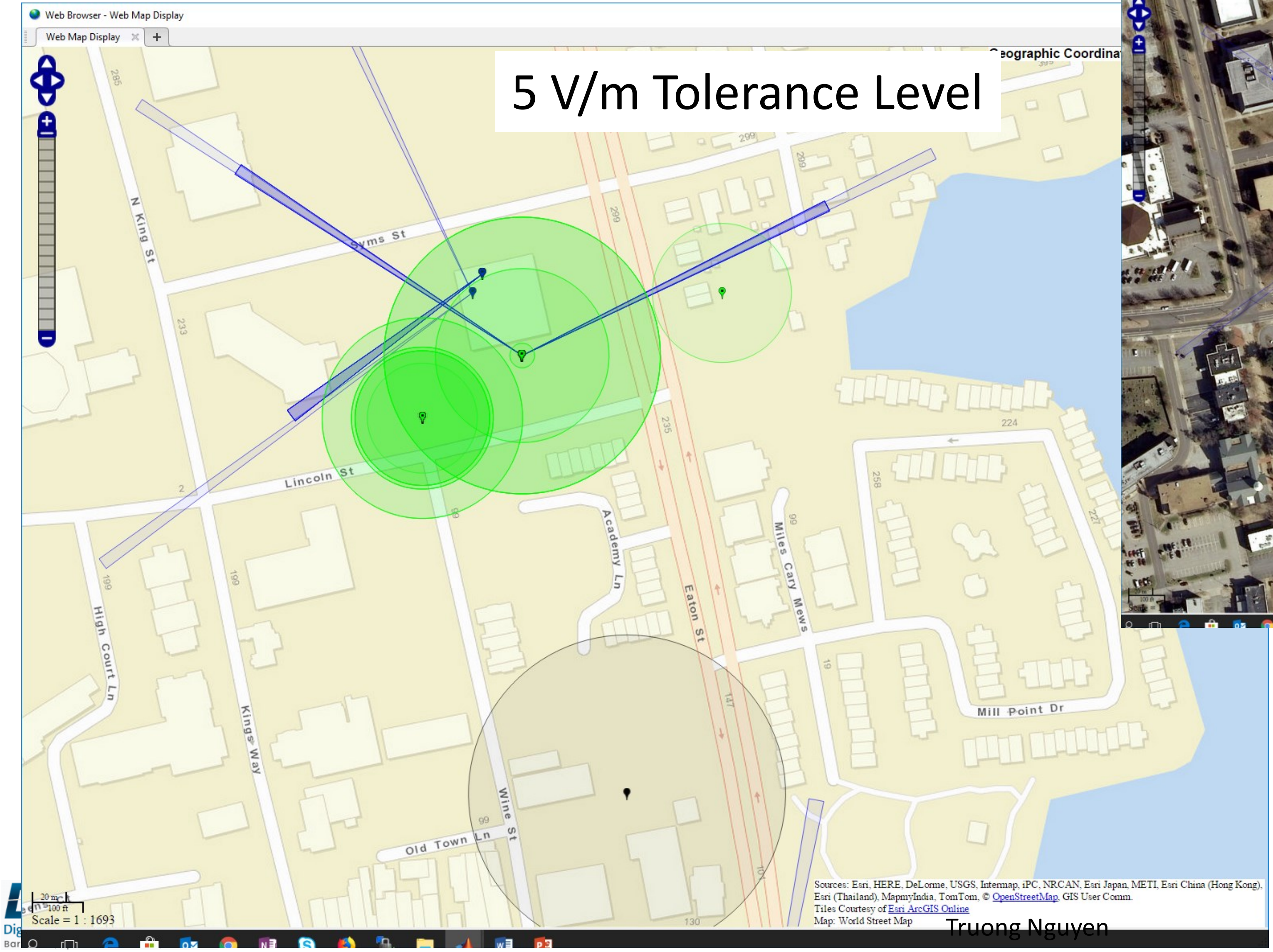
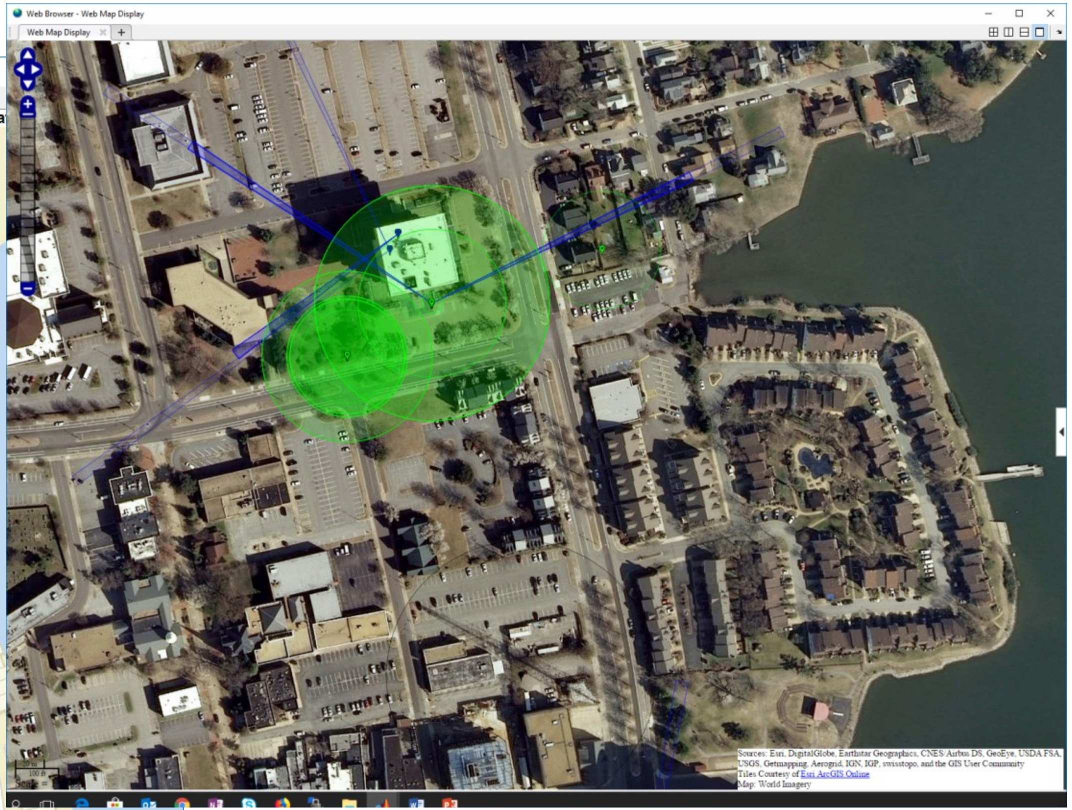
ULS Transmitters HIRF Zones, Hampton, VA





FCC ULS Transmitters

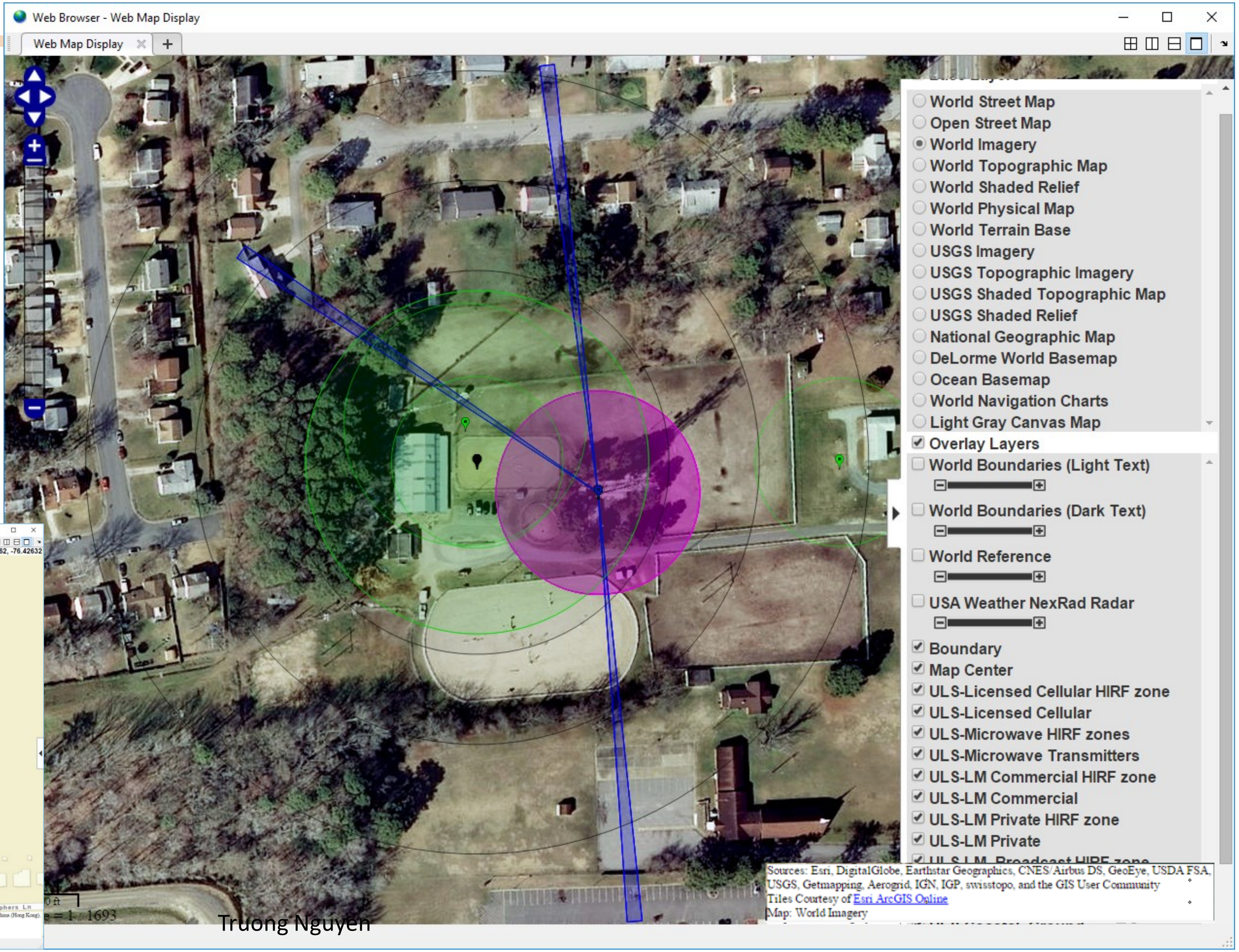
- Cellular
- Microwave
- Land Mobile
- Coastal and Aviation Ground
- Paging

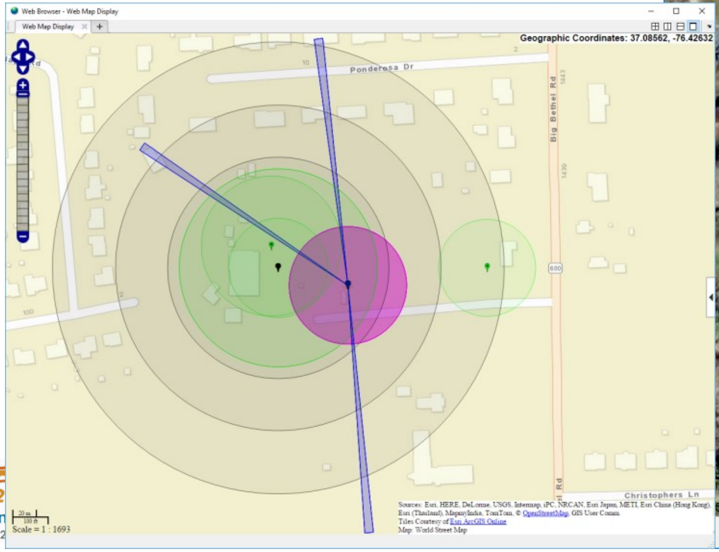
ULS Transmitters HIRF Zones Example

Location: Hampton, VA
Vehicle Tolerance Level: 2 V/m

FCC ULS Transmitters

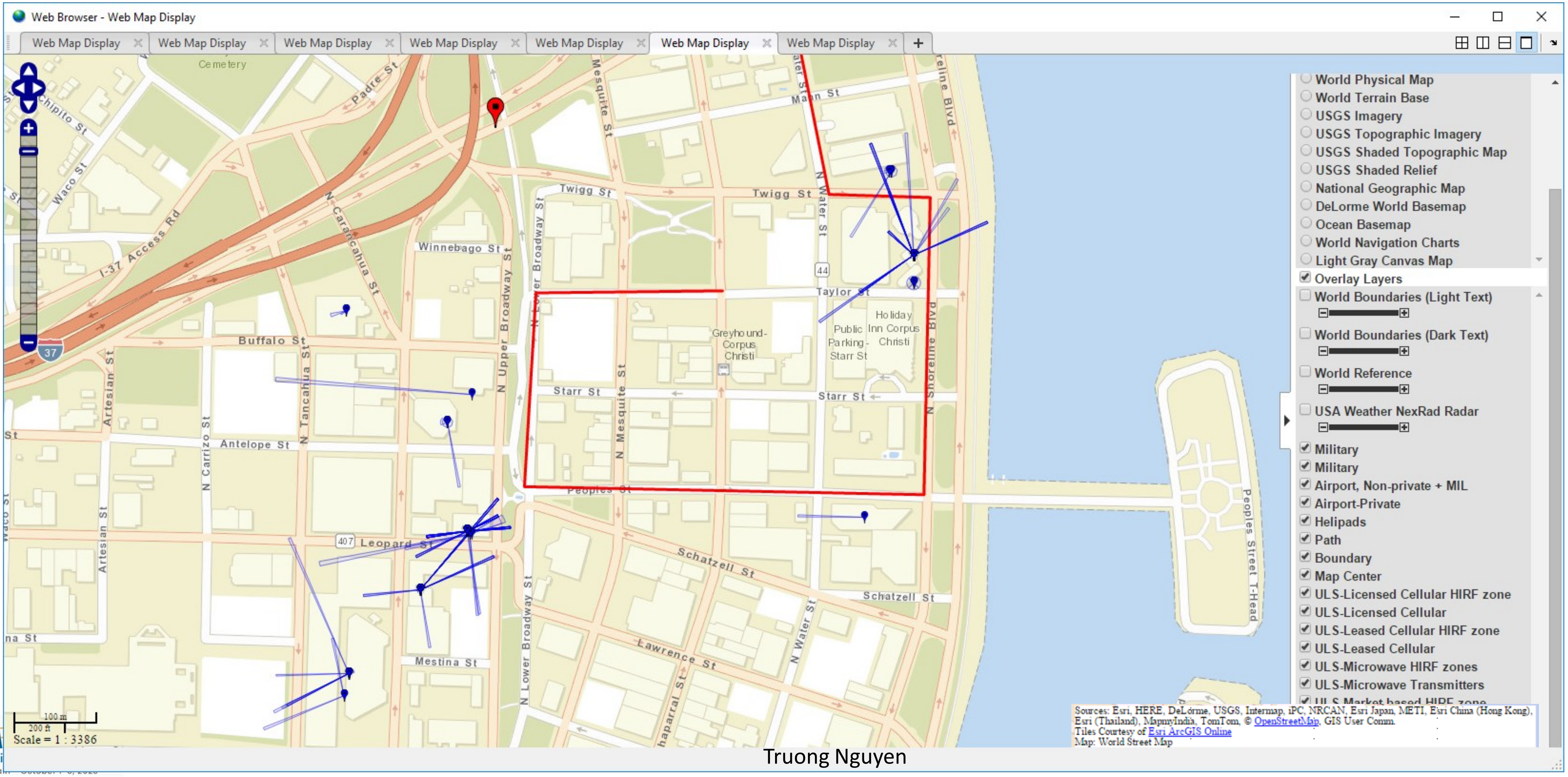
- Cellular
- Microwave
- Land Mobile
- Coastal and Ground
- Paging





Flight Path Planning Example – Microwave links

- <u>Location</u>: Corpus Christi, Texas; 5 V/m tolerance



Cellular Base Stations

$$R = \frac{1}{E}\sqrt{30PG}$$

- Cellular Base Station Safe Distance
  - Assume *EIRP* = *PG* = 120 Watts
  - For R =1*m*, ➔ *E* = 60 V/m

➔To allow the vehicle to be as close as 1m from a cellular base station, it needs to tolerate 60 V/m field strength.

Safe Distance Calculations
for a 120-watt EIRP Source

E (V/m)	Distance R (m)
5	12
10	6
20	3
30	**2**
50	1.2
60	**1**
100	0.6
120	0.5

NOAA Weather Radars

	NEXRAD (WSR-88D)
Frequency	2700-3000 MHz
Peak Power	750 kW
Power Gain	45.5 dB
Beam Width	0.95 degrees
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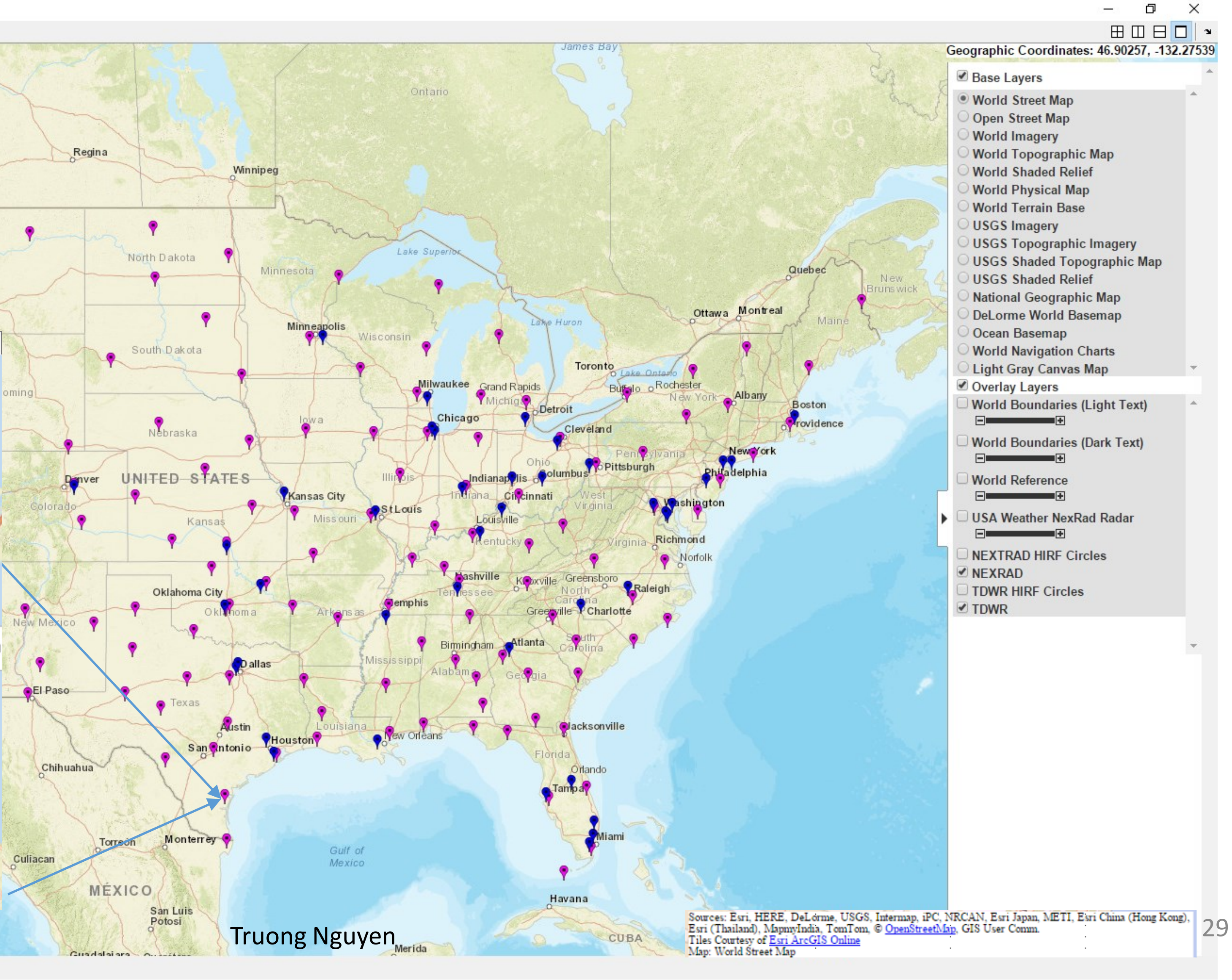

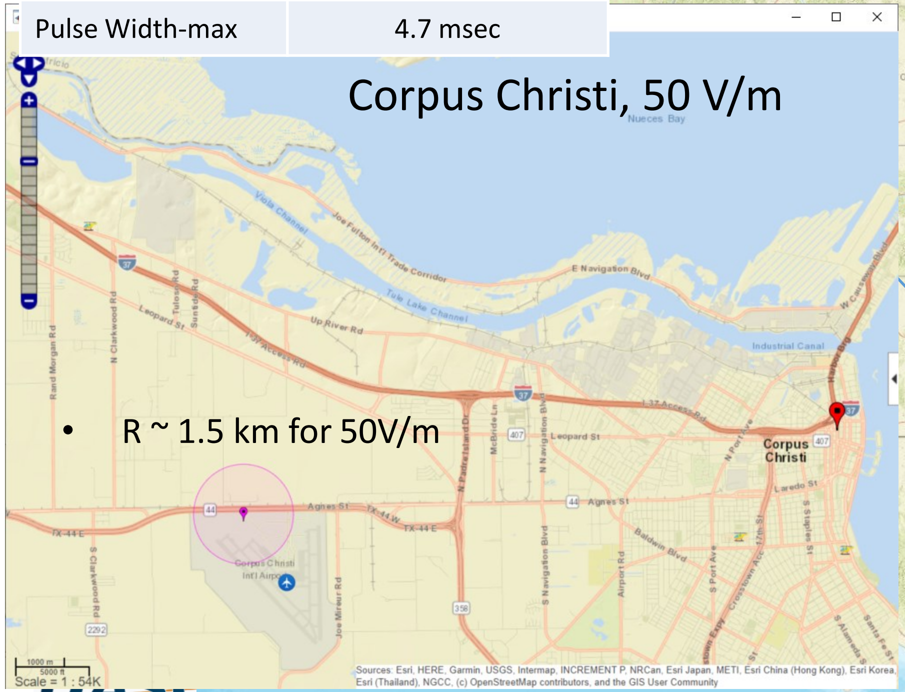

Corpus Christi, 50 V/m

- R ~ 1.5 km for 50V/m

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Findings

- GPS accuracy of CDBS and IBFS databases could be improved
  - Some **GPS data rounded** to seconds–
    - Accuracy can be off ~30 meters
  - **GPS location of the facility**, instead of the antenna
- Many SES have no transmitter power info
- ULS Databases:
  - <u>Numerous low-power transmitters </u>in a small region
  - Accurate GPS data
  - Cellular data far from complete
    - FCC no longer maintains the cellular database

  ➔ <u>Recommend a default minimum HIRF tolerance</u>

Conclusions

- The HIRF-avoidance approach appears **technically feasible**
- **Improvements to GPS accuracy of FCC CDBS and IBFS databases** are desirable
- Recommend a low-level **default tolerance level for ULS sources,** including cellular base stations
- **Avoid airports and military/government installations for now** unless transmitter databases are available

Recommendations

- **Establish a standard subgroup** to further develop, and coordinate with national authorities (FAA, NTIA) on <u>sensitive</u> transmitter databases access
  - **Establish a Gate-keeper**
    - An authorized entity for sensitive data
    - Provide HIRF Maps capabilities for government and airport sites, or
    - Provides sanitized data for use in HIRF maps
  - **Sanitized data expected form:**
    - **Frequency:** Fit frequency to one of the **frequency segments (FS1 - FS17)**
    - **Power Level**: Round up to one of the **power band segments** (TBD)
    - **Modulation**: Down-select to **CW, AM, or Pulse classification** only
    - **GPS Location**: **<u>Approximated location</u>**, and include uncertainty figure for map purposes

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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

Recommendations (Cont.)

- **Define vehicle <u>default minimum tolerant levels</u>** <u>based on</u>
  - ULS's statistics of each transmitter type
  - Tolerant to unlicensed transmitters
  - Tolerant to other AAM vehicles' transmitters
- **Work with the FCC to improve CDBS and IBFS GPS accuracy**
  - As FCC licenses are renewed periodically
- **Avoid airports and military/government sites for now**
- Incorporate additional databases if available
  - Airport Surveillance Radar, Air-Route Surveillance Radar,…

The End

System-Wide Safety (SWS) Project

Electrified Powertrain Flight Demonstration Project

DASC 42nd Digital Avionics Systems Conference
Barcelona, Spain - October 1-5, 2023

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Map Attributions

- Google Maps
- Matlab WebMap
- Sources for WebMap: 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.
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