MIT ICAT

MIT International Center for Air Transportation

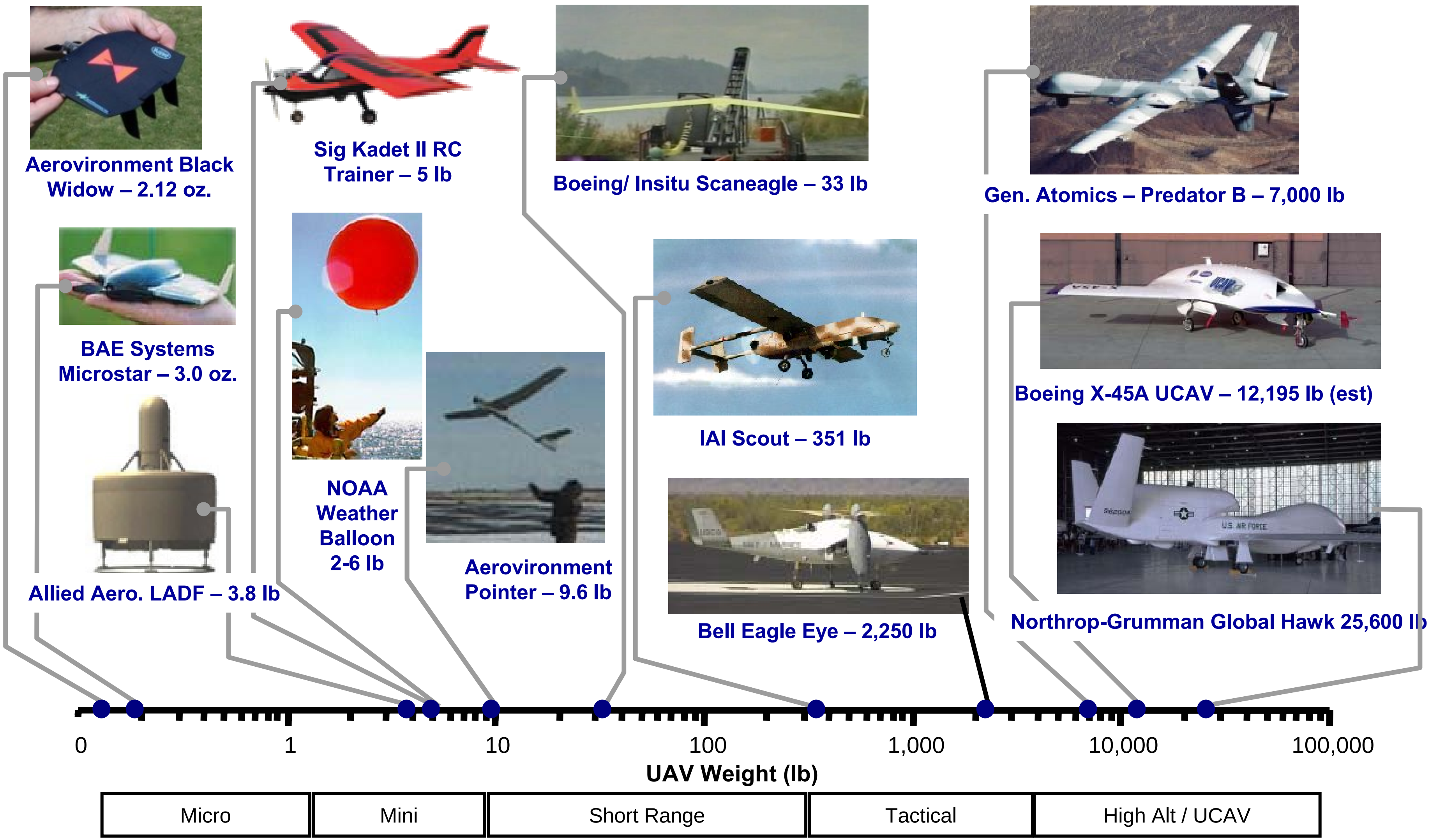
Safety Considerations for Operation of Small Unmanned Aerial Vehicles in Civil Airspace

R. Weibel & R. John Hansman

MIT Joint University Program
Quarterly Meeting

23 October 2003

Current Unmanned Aerial Vehicles



Motivation

- **Unmanned Aerial Vehicles (UAVs) provide public benefit for a variety of applications**
  - National Defense
  - Disaster Response
  - Homeland Security/ Law Enforcement
  - Traffic Surveillance
  - Weather Monitoring
  - Communications Relay
- **Military operations raised awareness**
  - Utilized successfully in several recent conflicts – Kosovo, Afghanistan, Iraq
- **Commercial/Civil applications have been demonstrated**
  - Test flights over coffee plantation in Hawaii and winery in California
  - Coast Guard order for up to 69 Eagle Eye tilt-rotor UAVs for maritime surveillance as part of Deepwater program
- **Large opportunities exist for small-scale UAV's**
  - Miniaturization trend in electronic equipment; sensors, datalink, etc.
  - Investigation required for influence of vehicle mass on risk

Problem Statement

- **Lack of rules/ regulations creates barrier to commercial operations**
  - Lengthy certificate of authorization (COA) process for UAV flight approval in NAS

- **Current federal air regulations did not anticipate operation of controlled unmanned aircraft in civil airspace**
  - No specific part or definition related to unmanned aircraft
  - Safety analyses presume safety of occupants of aircraft guarantees safety of public on ground

Goal: Investigate concepts of operation and risk mitigation strategies that allow UAVs to be operated with minimal restrictions to achieve the maximum public benefit

Approach

- **Appropriate Standards**
  - Uncertainty over jurisdiction for UAV regulation, definition of aircraft
  - FAA methodology and safety targets used
- **Preliminary Safety Analysis for a Conceptual UAV System**
  1. Preliminary Examination/ Categorization of Possible Adverse Effects
  2. Estimation of risk of effects
  3. Identification and categorization of mitigation strategies to control risk
  4. Implications for restriction/ requirements for UAV operation
- **Critical Hazards Identified**
  - High energy ground impact
  - Mid-air collision with a another aircraft
- **Risk Quantified as a Function of UAV Mass**
  - Order of magnitude analysis to compare risk of critical hazards to target levels of safety
  - Determination of vehicle reliability to meet target level of safety

Target Level of Safety

- **Target Level of Safety (TLS) – the design criterion for probability of occurrence of adverse events**
  - Each event has a given classification of severity – catastrophic, hazardous, major, or minor
  - Each level of severity has a target level of safety associated with it
- **Relevant Classifications for Midair and Ground Exposure Risks**
  - Hazardous (TLS of 10^{-7} events/hour)
    - "Serious or fatal injury to small number of occupants of aircraft (except operators)"
    - "Fatal injury to ground personnel and/or general public"
  - Catastrophic (TLS of 10^{-9} events/hour)
    - "Results in multiple fatalities and/or loss of the system"
- **Uncertainty in Appropriate Target Level of Safety**
  - Analysis performed at TLS of 10^{-8} for ground exposure, order of magnitude greater than TLS for Hazardous

Preliminary Ground Fatality Probability Formulation

$$\frac{P(F)}{hr} = \frac{P(Inc)}{hr} P(Exp \mid Inc) P(F \mid Exp)$$

Where:

P(F)/hr is the *fatal accident rate*: the probability of fatal injury to a person on the ground per hour of flight – set by the target level of safety

P(Inc) is the *vehicle reliability:* the probability of an incident on the vehicle leading ground impact

P(Exp | Inc) is *exposure probability*: the area-based probability that a person on the ground is exposed to a lethal field of debris from the vehicle

$$P(Exp \mid Inc) = A_{exp}\rho$$

A_{exp} is the average area of lethality due to a UAV ground impact, approximated as the frontal area of UAV
ρ is the population density of the area, based on 2000 U.S. Census data

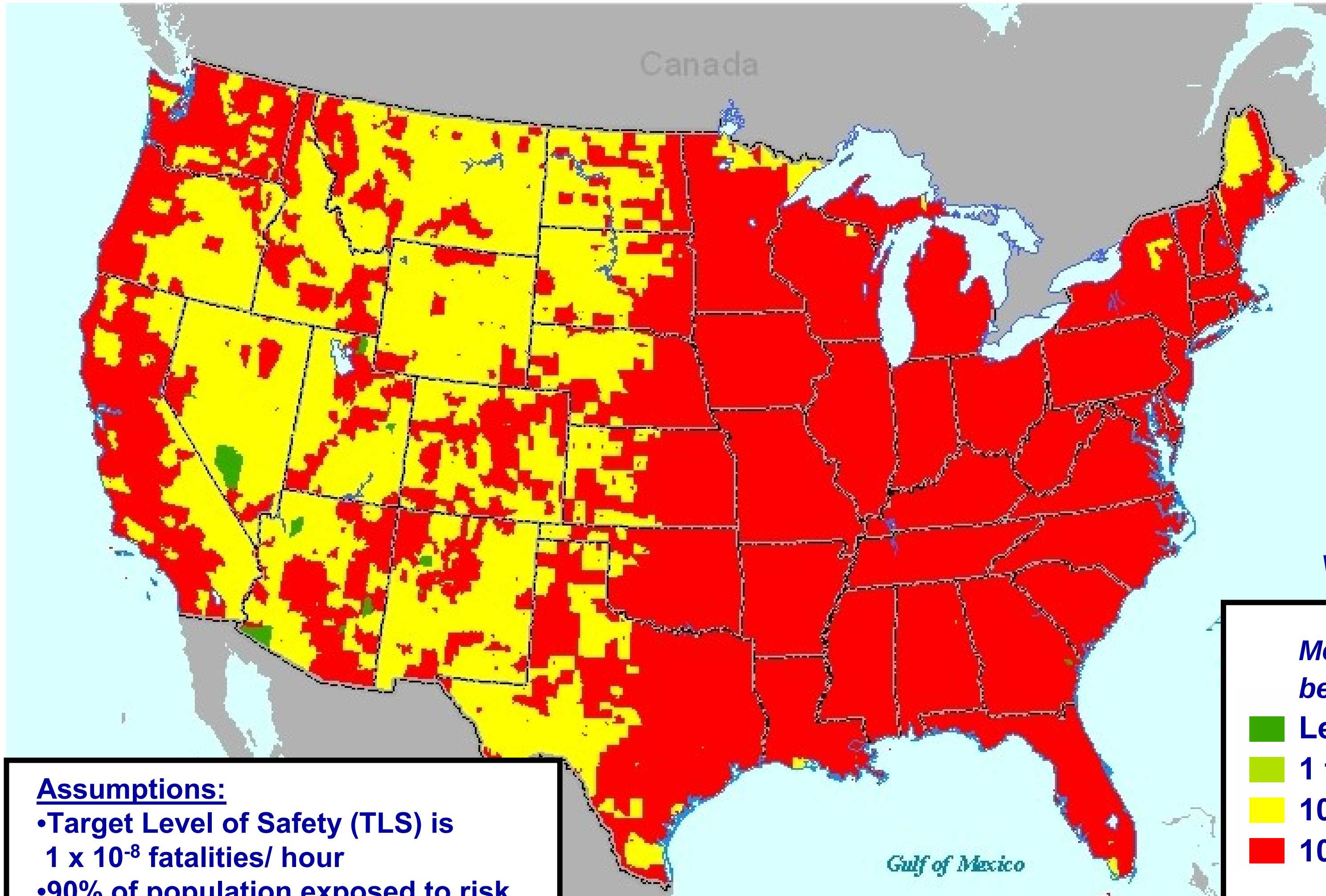
P(F | Exp) is the *(un)protection factor*: the probability of fatal injury given the exposure to a lethal vehicle debris field

- **Estimated as a percentage of the population exposed to the vehicle at any point in time, recognizing that some persons will be protected by vehicles or buildings**

Ground Exposure Analysis

Vehicle		*Weight*	*Frontal Area*	*P(F | Exp)*
Northrop Grumman Global Hawk		**25,600 lb**	**970 ft^2**	**90%**
IAI Scout		**351 lb**	**5 ft^2**	**25%**
Aerovironment Pointer		**9.6 lb**	**1.7 ft^2**	**10%**
Aerovironment Black Widow		**0.14 lb (2.16 oz)**	**0.26 ft^2**	**5%**

Global Hawk Reliability Requirements to meet TLS of 10^{-8} /hr



Northrop-Grumman Global Hawk - 25,600 lb

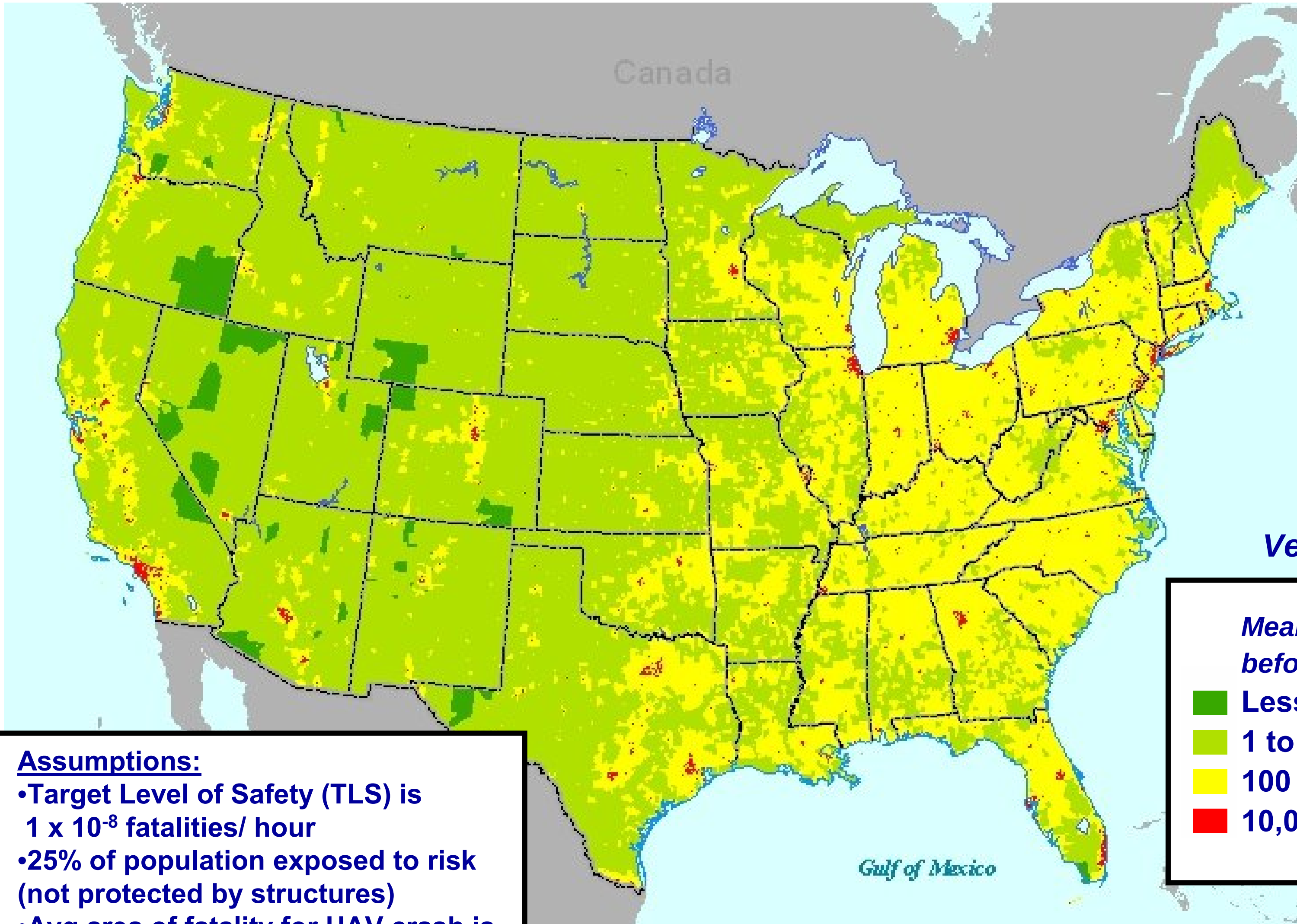
Vehicle Reliability

Mean op. hours before failure	*% of US by Area*
Less than 1 hr	6.3%
1 to 100 hr	0.0%
100 to 10,000 hr	37.7%
10,000 hr and up	56.0%

Assumptions:

- Target Level of Safety (TLS) is 1×10^{-8} fatalities/ hour
- 90% of population exposed to risk (not protected by structures)
- Avg area of fatality for UAV crash is 970.0 ft^2

Scout Reliability Requirements to Meet TLS of 10^{-8} /hr



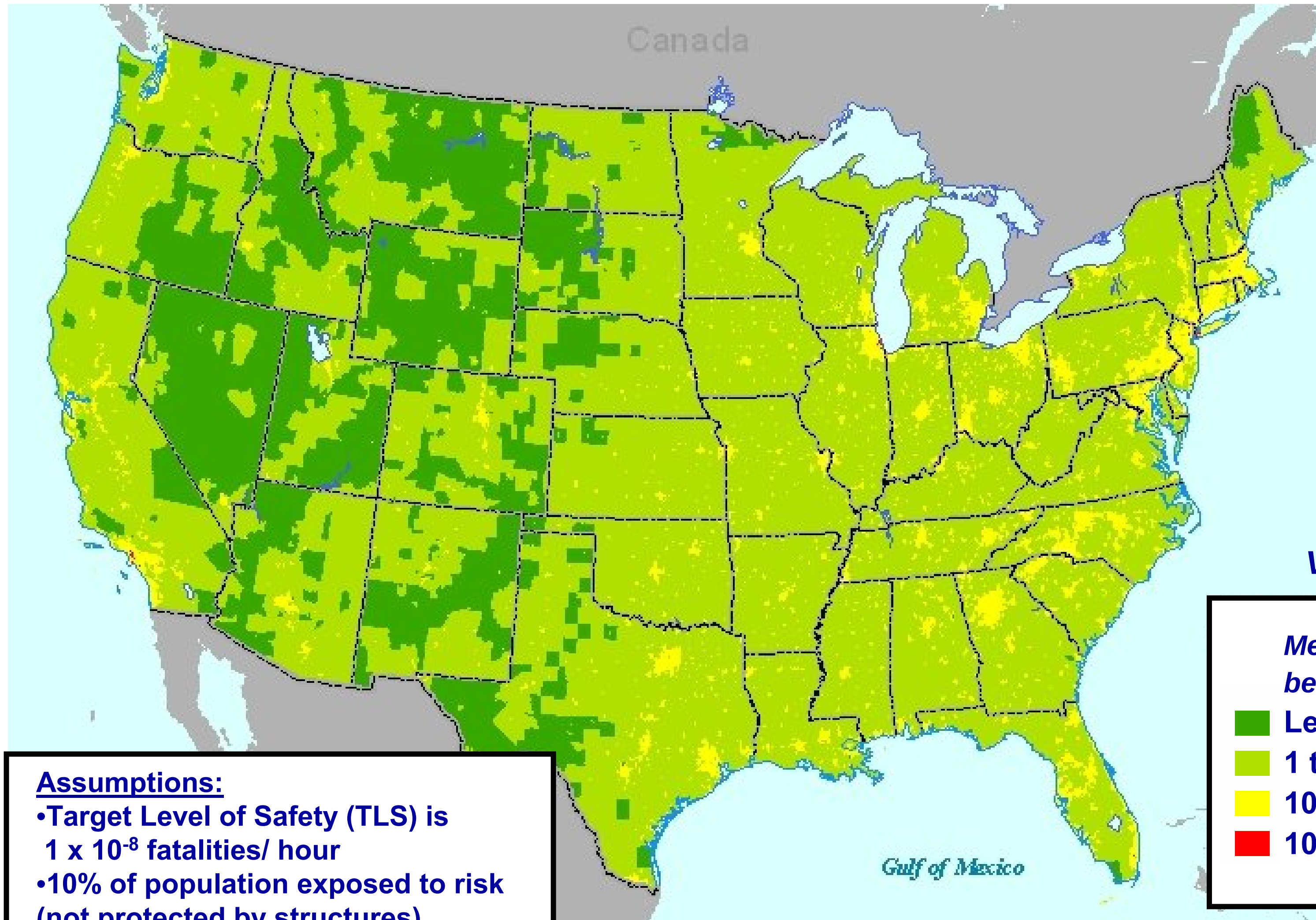
IAI Scout – 351 lb

Vehicle Reliability

	Mean op. hours before failure	*% of US by Area*
(dark green)	Less than 1 hr	14.8%
(light green)	1 to 100 hr	58.1%
(yellow)	100 to 10,000 hr	26.4%
(red)	10,000 hr and up	0.7%

Assumptions:
- Target Level of Safety (TLS) is 1×10^{-8} fatalities/ hour
- 25% of population exposed to risk (not protected by structures)
- Avg area of fatality for UAV crash is 5.0 ft^2

Pointer Reliability Requirements to meet TLS of 10^{-8} /hr



Aerovironment Pointer – 9.6 lb

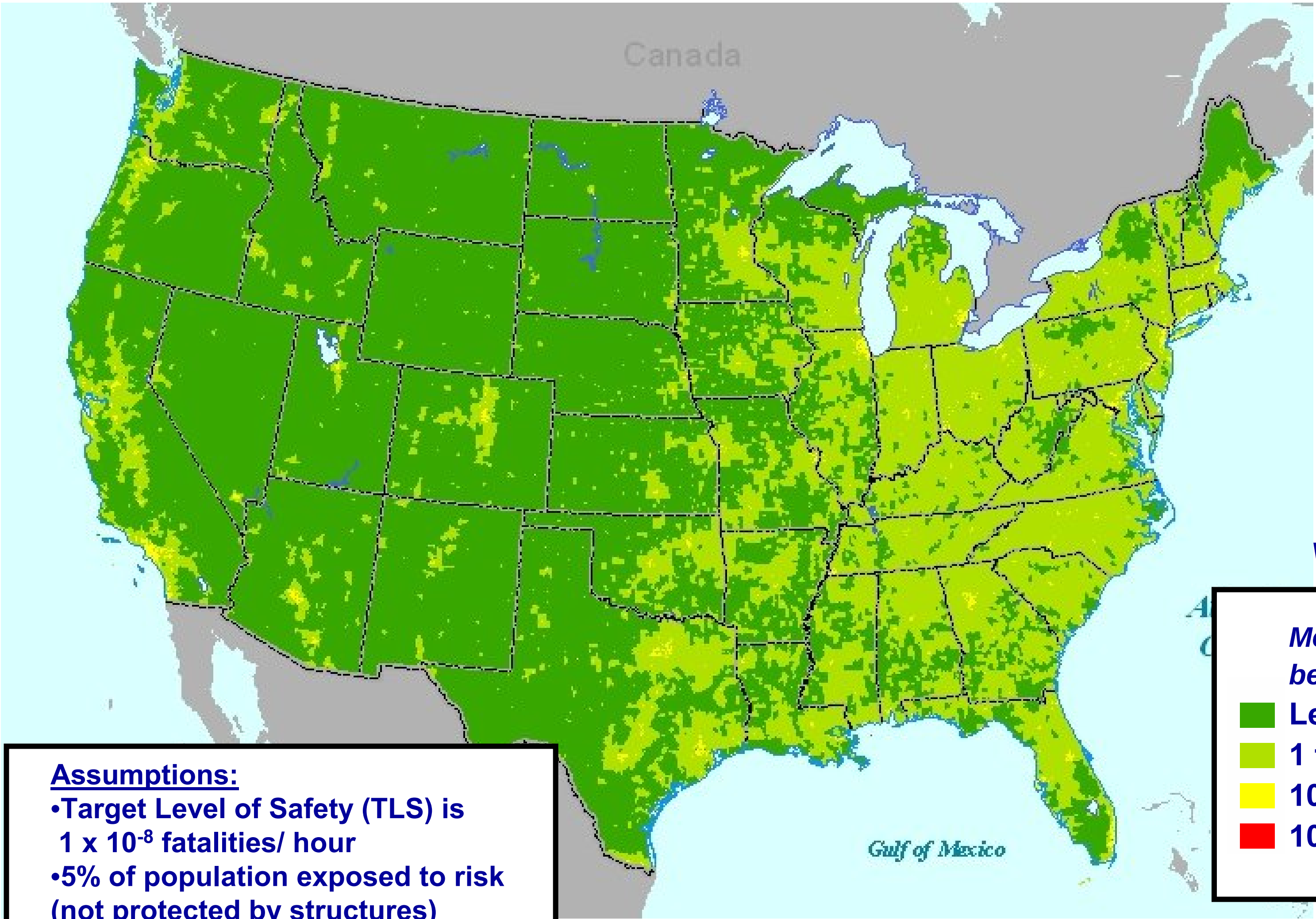
Vehicle Reliability

	Mean op. hours before failure	*% of US by Area*
(dark green)	Less than 1 hr	34.0%
(light green)	1 to 100 hr	60.8%
(yellow)	100 to 10,000 hr	5.2%
(red)	10,000 hr and up	0.02%

Assumptions:

- Target Level of Safety (TLS) is 1×10^{-8} fatalities/ hour
- 10% of population exposed to risk (not protected by structures)
- Avg area of fatality for UAV crash is $1.7\ ft^2$

Black Widow Reliability
Requirements to meet TLS of 10^{-8} /hr



Aerovironment Black Widow – 2.12 oz.

Vehicle Reliability

	Mean op. hours before failure	*% of US by Area*
Green	Less than 1 hr	72.4%
Light green	1 to 100 hr	26.8%
Yellow	100 to 10,000 hr	0.7%
Red	10,000 hr and up	0.01%

Assumptions:

- Target Level of Safety (TLS) is 1×10^{-8} fatalities/ hour
- 5% of population exposed to risk (not protected by structures)
- Avg Human Vulnerable Area is 0.26 ft^2, UAV frontal area is 0.02 ft^2

Preliminary Midair Exposure Risk Analysis Method

- **Source**
  - Enhanced Traffic Management System (ETMS) Aircraft Surveillance Data for a typical weekday (January 9th 2003)
- **Assumptions**
  - Uniform distribution of flights from 0 to 10,000 ft MSL
  - Uniform distribution of flights horizontally
  - Uniform distribution of flights throughout the day
  - Velocity of threatened aircraft large compared to UAV cruise speed, can therefore treat UAV as static
  - Threatened aircraft completely transverses airspace segment within hour
  - Exposure area of threatened aircraft is equal to the frontal area of a Boeing 757
- **Formulation**
  - From the UAV perspective, several airplanes transit through the airspace creating exposure volumes
  - If the exposure volume intersects the UAV, a collision has occurred

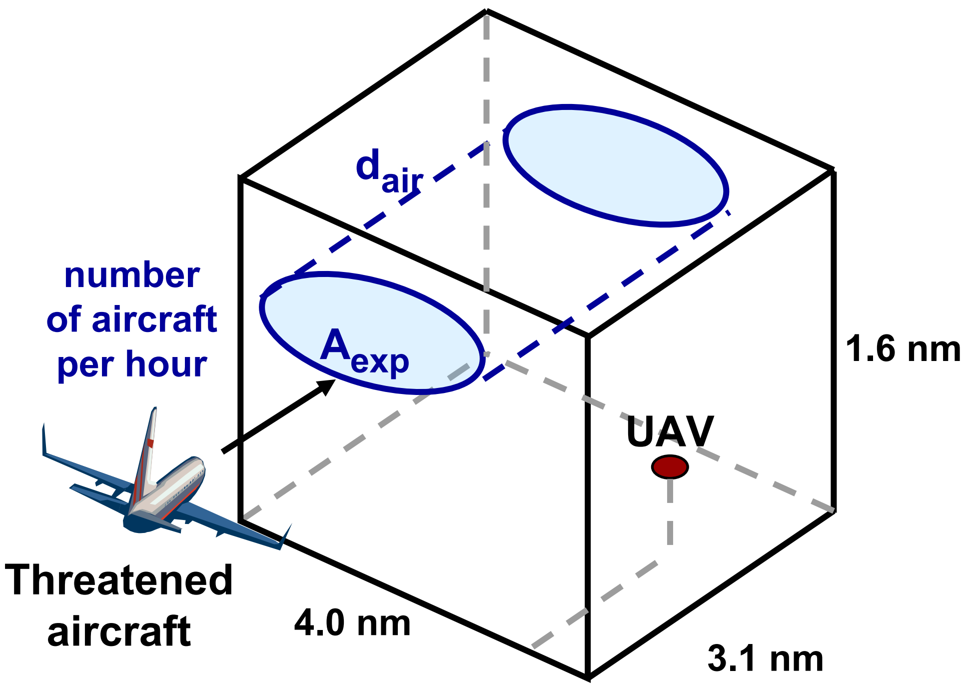
Preliminary Midair Exposure Risk Formulation

$$\frac{N(C)}{hr} = \frac{N(a/c)}{hr}\frac{V_{exp}}{V_{air}}$$

Where:

N(C)/hr is the ***collision rate***: set by the target level of safety

N(a/c)/hr is the ***rate of aircraft through the airspace:*** sets the number of times the exposure area will sweep through the airspace



V(exp) is the ***exposure volume***

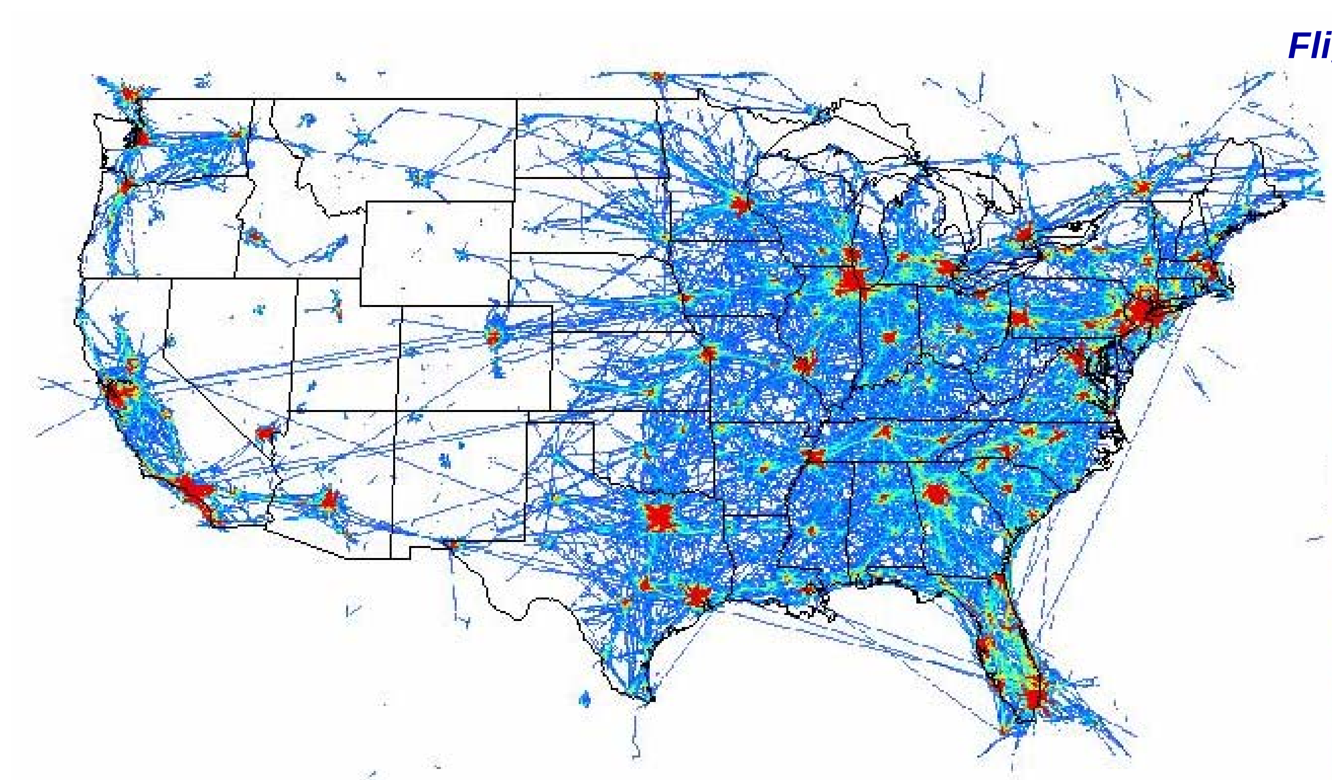
$$V(exp) = A_{exp} d_{air}$$

A_{exp} is the **vulnerable area** of the threatened aircraft in a collision with the UAV

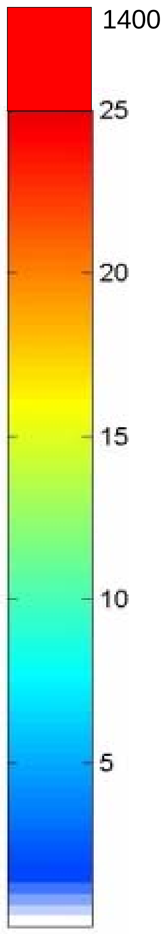
d_{air} is the **distance travelled** by the threatened aircraft through the airspace

V(air) is the ***volume of the airspace segment***

Midair Collision Risk Results



Flights/ Day



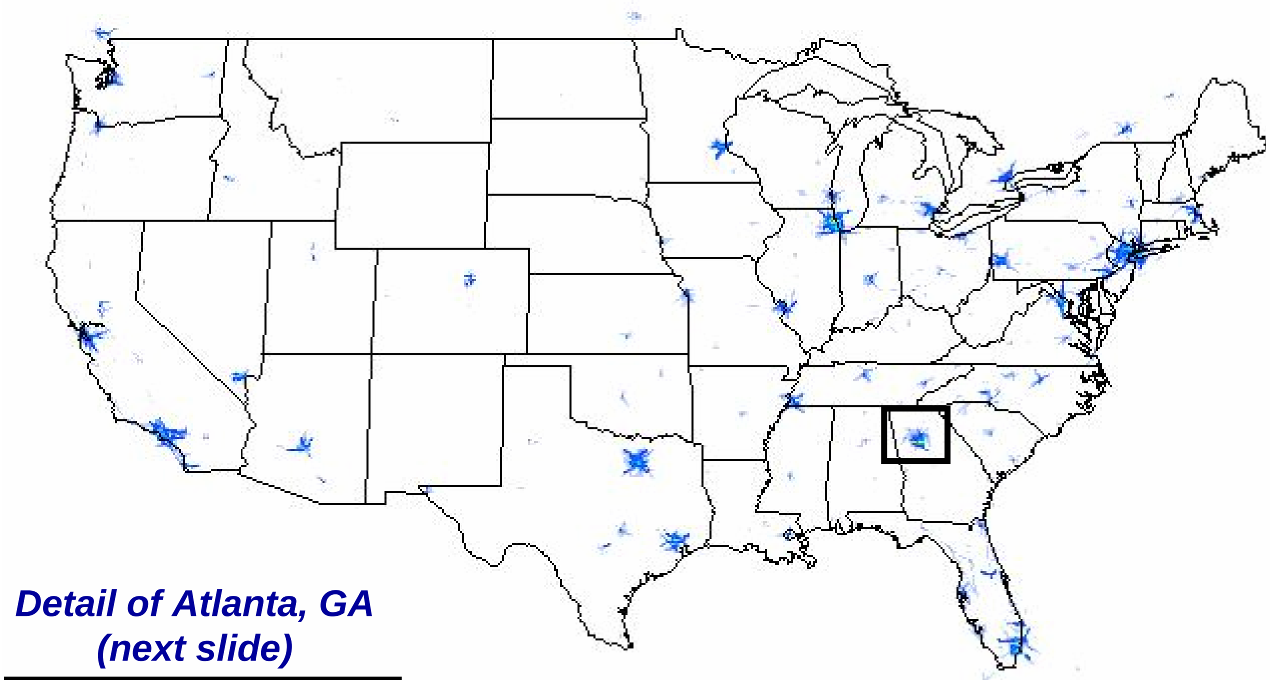
Collision Rate
3.6 E-08 / hr
6.4 E-10 / hr
2.6 E-11

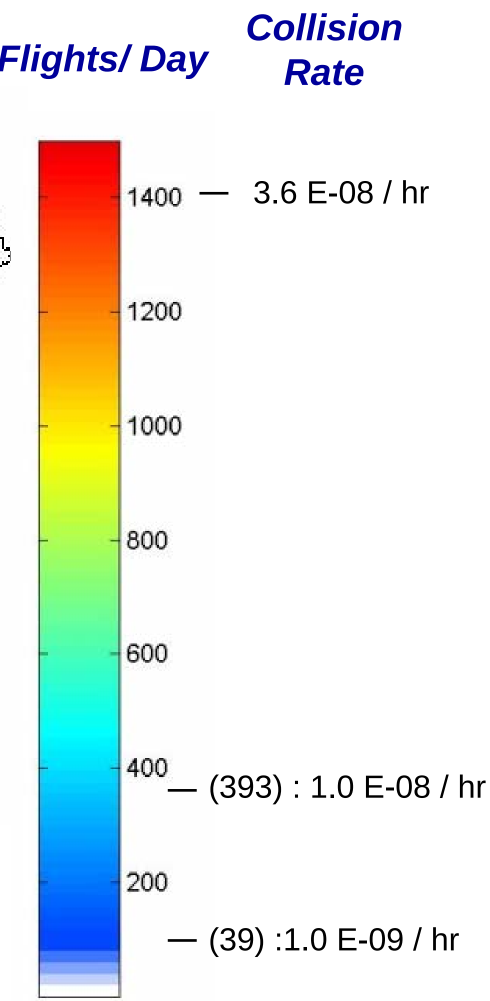
Assumptions:

- **Uniform distribution of flights from 0 to 10,000 ft.**
- **Other traffic average size of Boeing 757**
- **Vulnerable area for hazardous event is frontal area of 757 (560 ft^2)**

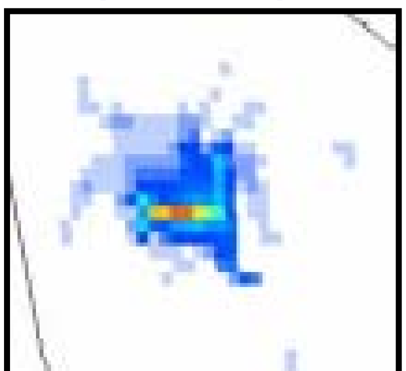
Air Traffic Density Data Courtesy of A. Mozdzanowska

Midair Collision Risk Results





Detail of Atlanta, GA (next slide)



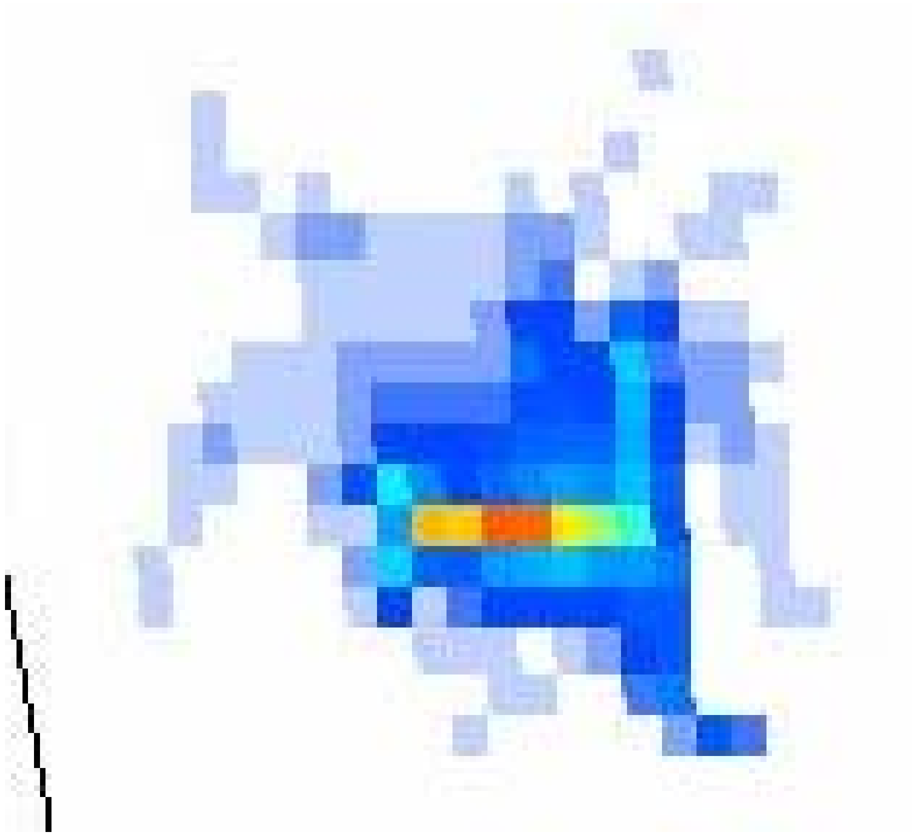
Assumptions:

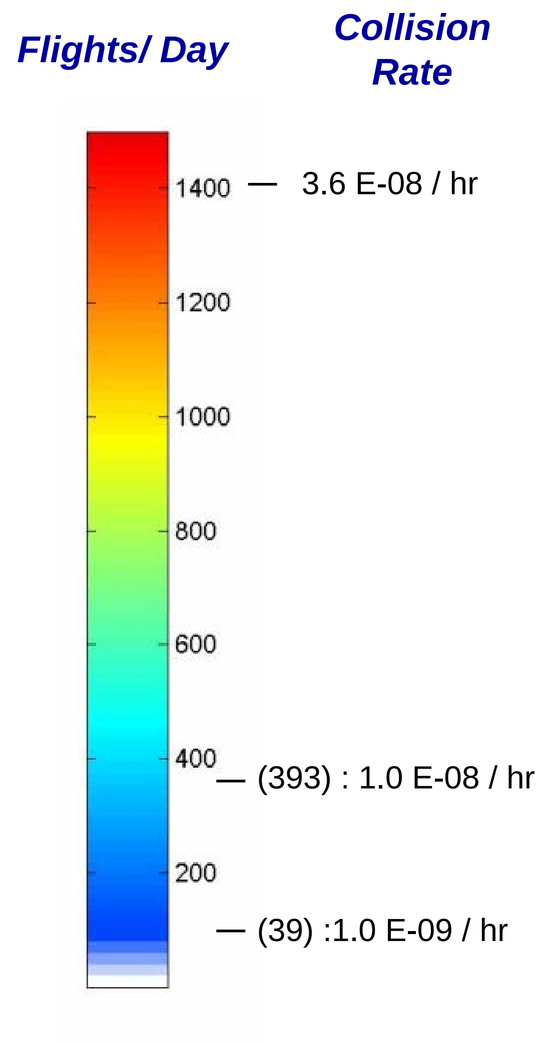
- **Uniform distribution of flights from 0 to 10,000 ft.**
- **Other traffic average size of Boeing 757**
- **Vulnerable area for hazardous event is frontal area of 757 (560 ft^2)**

Air Traffic Density Data Courtesy of A. Mozdzanowska

Midair Collision Risk Results
Atlanta, GA

Detail of Atlanta, GA





Conclusions

- **Significant Area of U.S. with Ground Exposure Risk Below the Target Level of Safety for small UAVs**
  - Risk increases with vehicle mass
- **Significant Amount of Airspace with Exposure Risk Below the Target Level of Safety**
  - Areas around major airports are above the target level of safety
  - Risk Does not vary significantly with mass for small vehicles
- **Opportunities may exist to allow a class of small UAV's to operate with limited restrictions**
  - Limiting operation in airspace near airports or over congested areas may achieve target level of safety
- **Mitigation Strategies Are Available to Further Reduce the Risk**
  - Vehicles can be designed with capabilities to limit energy of impact or likelihood of midair collisions or ground impact

Preliminary Mitigation Possibilities

- **Design/ Maintenance**
  - Sets reliability of components/ frequency of failures, mass and energy of accident
- **Operator Intervention**
  - Skill level of operator influences recovery from failures and safety of routine operation
- **Emergency Management**
  - Vehicle systems that reduce energy of impact given a loss of vehicle – parachutes, flight termination, autorotation
- **Operating Restriction**
  - Ensures that when a failure occurs, less likely to impact general public
- **Building/ Other Aircraft Response**
  - Determines how likely it is that destruction of UAV will harm other people or property

On-Vehicle Protection

Extra-Vehicular Protection