Safety risk posed to persons on the ground by commercial UAS-based services
- Learning from airports and hazardous installations -

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Motivation

Commercial UAS-based Operation

➢ Offers service to public or company

    ➢ Parcel delivery service, etc.

    ➢ Air mobility service

➢ Within a certain area

➢ Makes use of multiple UAS (types)

➢ Conducts N UAS flights per year

Societal Issues [EASA, 2021]:

➢ Safety Risks

➢ Noise Hindrance

➢ Privacy

➢ Security and Cyber-security

➢ Visual Pollution

➢ Other Environmental Pollution

Unresolved Gap

Societal issues are more severe for areas with more potential customers

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Third Party Risk (TPR) Indicators

Impact on Requirements

Last-mile Delivery Examples

Conclusions

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TPR Indicators in Commercial Air Transport

- **Flight TPR**: Expected # of external fatalities per flight (or flight hour)

  = Small Part of Expected # of fatalities per flight (or flight hour)

- **Societal risk** indicators:

  - **FN-curve**: *) Probability of n or more ground fatalities per annum

  - **Collective risk**: *) Expected # of ground fatalities per annum

- **Individual risk** *): Annual probability that an unprotected person at location y is being killed due to an accident

*) Indicator and acceptability criterion is in use for Hazardous Facilities and Airports

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3rd Party definitions differ

Commercial Air Transport
3rd Party = People exposed
for reasons unrelated to the
flight [Eurocontrol, 2015]

→ Public on the ground

UAS
3rd Party = People not associated
with, nor deriving direct benefit
from the flight [Clothier et al., 2018]

→ Public on the ground
+ Passengers in another air vehicle

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Extending TPR indicators from CAT to UAS

Collective ground risk per flight
$$R^i_{Cground}$$

Expected number of third party fatalities in a given area X due to the direct consequences of i-th UA flight accident.

Per flighthour
$$R^i_{Cground} / T_i$$

Collective ground risk
$$R^{UAS}_{Cground}$$

Expected number of third party fatalities on the ground in a given area X due to the direct consequences of UA flight accidents during a given annum.

$$R^{UAS}_{Cground} = \sum_{i=1}^{N} R^i_{Cground}$$

Individual risk
$$R^{UAS}_I(y)$$

Probability that an average unprotected person, who resides permanently at ground location y, would get killed due to the direct consequences of UA flight accidents during a given annum.

$$R^{UAS}_I(y) = \sum_{i=1}^{N} R^i_I(y)$$

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Acceptability Thresholds for the three UAS TPR indicators

- Collective Ground Risk per flighthour
  → Equivalent Level of Safety (ELOS)

$$R^i_{Cground} / T_i \leq C_{ELOS}$$

- Collective Ground Risk (CGR)

$$R^{UAS}_{Cground} \leq C_{CGR}$$

- Individual Risk (IR)

$$R^{UAS}_I (y) \leq C_{IR}$$

Each acceptability threshold yields a requirement on Overall UAS System Failure rate λ_E

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**From ELOS, CGR and IR Acceptability Thresholds
to Requirements on Overall UAS System Failure rate** λ_E

Two methods:
1. Monte Carlo simulation of UAS operation [Blom et al., RESS 2021]
   - Illustrated for a hypothetical UAS-based parcel delivery service
2. Analytical characterization for Parcel delivery under model assumptions:
   - Homogeneity assumptions of Melnyk et al. (2014)
   - Circular area around delivery centre
   - Expected number of parcel deliveries is the same for each inhabitant
   - Delivery flight follows direct radial paths
   - Crash centre is uniformly distributed along and Gaussian across radial.

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Method 2: Derivation of ELOS, CGR and IR based Requirements on λ_E as functions of model parameters θ

ELOS based yields $\qquad$ $\lambda_E \leq C_{ELOS} / f_{ELOS}(\theta)$

CGR based yields $\qquad$ $\lambda_E \leq C_{CGR} / f_{CGR}(\theta)$

IR based yields $\qquad$ $\lambda_E \leq C_{IR} / f_{IR}(\theta)$

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Effect of model parameters on ELOS, CGR and IR based λ_E^{-1} requirements

Parameter	ELOS-based	CGR-based	IR-based
Size of Crash area	Linear	Linear	Linear
Prob of Fatality	Linear	Linear	Linear
Population density	Linear	Quadratic	Linear
Prob of no Shelter	Linear	Linear	-
$\overline{n}$ = Mean # deliveries/annum	-	Linear	Linear
R = Delivery radius	-	Cubic	Quadratic
Radius of Zone	-	-	~Inverse linear
UAS cruise speed	-	Inverse linear	Inverse linear

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Effect of increasing mean number $\overline{n}$ of annual parcel deliveries per person ?

Parameter	Value
R = Delivery radius	3146 m
Radius of Zone	100 m
UAS cruise speed	15 m/s
Size of Crash Area	1 m^2
Prob of Fatality	1
Prob of no Shelter	0.1

Area type	Number of persons
Urban	1.2×10^5
Metropolitan	3.0×10^5
Metro City Center	8.4×10^5

Criterion	Value	Source
C_{ELOS}	0.76×10^{-7} per flight hour	Clothier & Walker (2006)
$C_{CGR} = C\pi^2 / 6$	$C = 10^{-3}$ per annum	FN criterion for 1 or more ground fatalities
C_{IR}	1×10^{-6} per annum	Individual Risk criterion in multiple countries

Urban area
ELOS, IR and
CGR based λ_E
requirements
as function of $\overline{n}$

Break even:

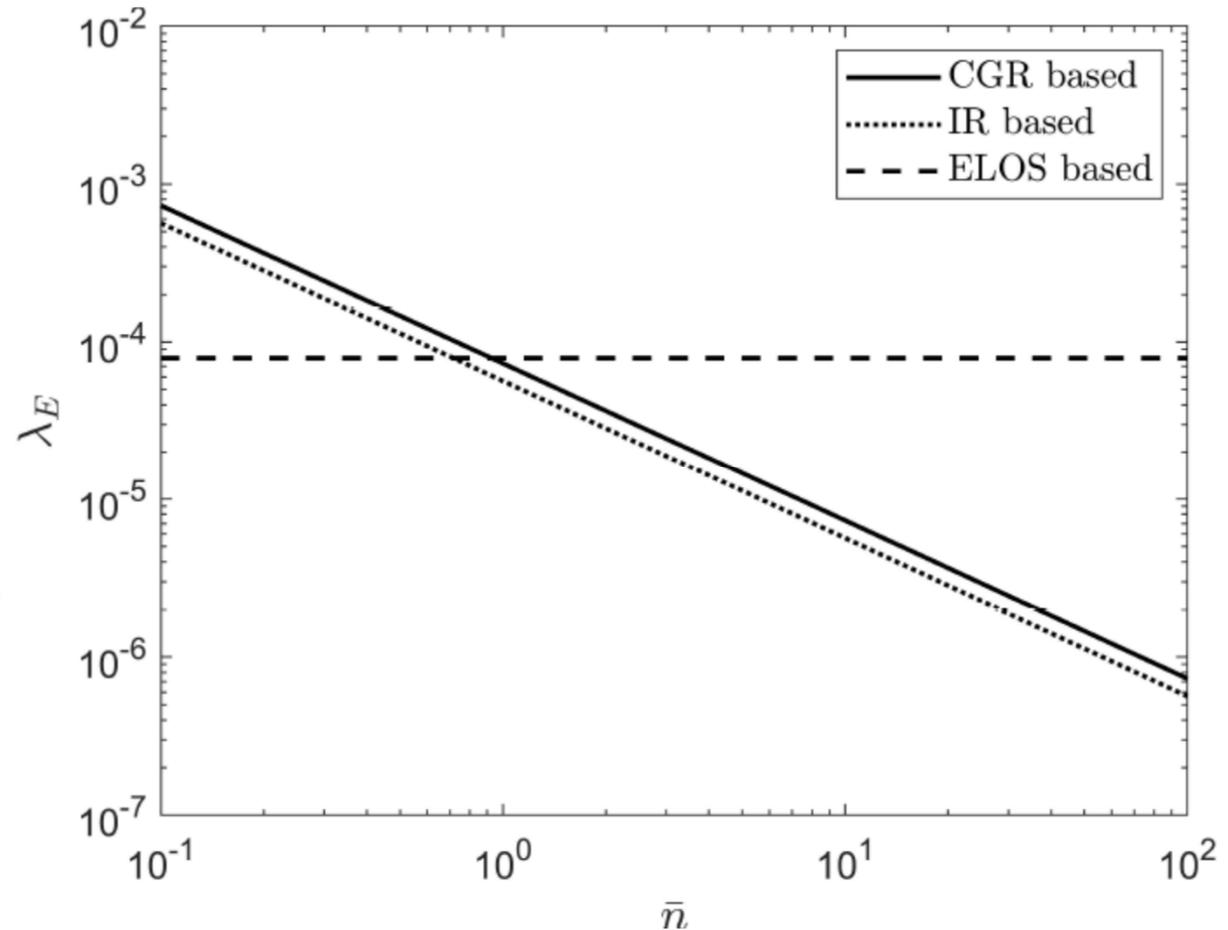CGR = ELOS: $\overline{n} = 2.44$
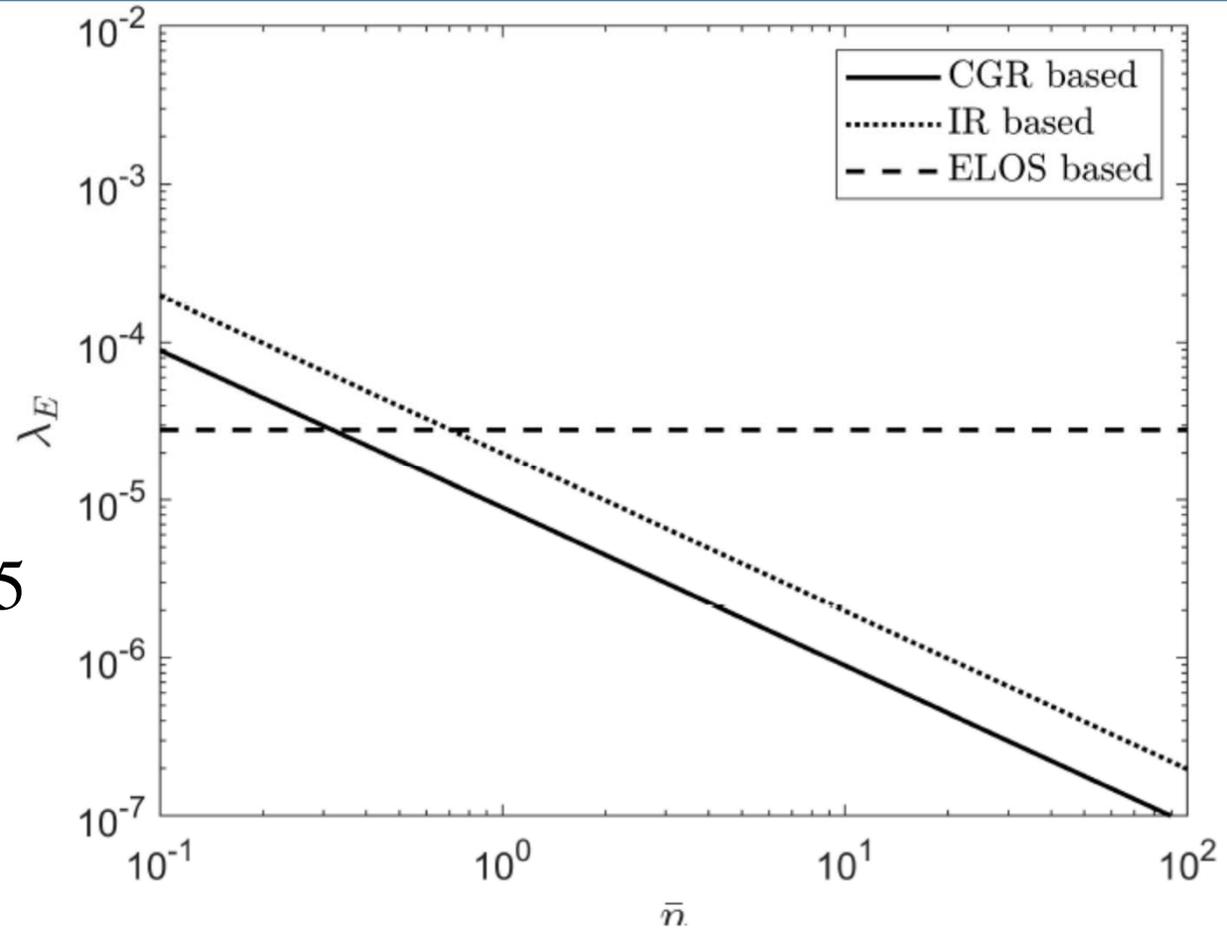
IR = ELOS: $\overline{n} = 0.8$

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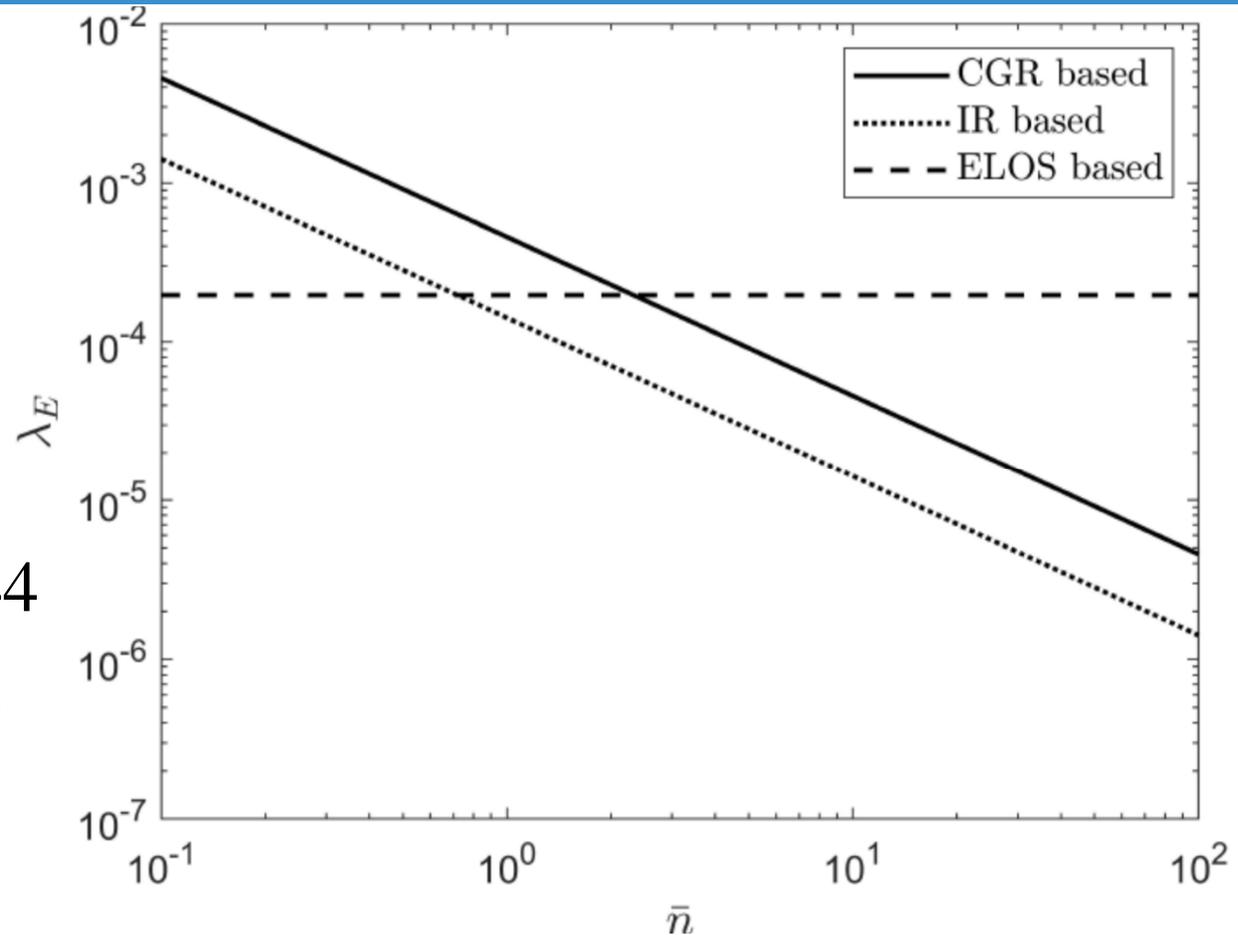
Metropolitan area
ELOS, IR and
CGR based λ_E
requirements
as function of $\overline{n}$

Break even:

CGR = ELOS: $\overline{n} = 0.98$

IR = ELOS: $\overline{n} = 0.8$

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Metro City Center
ELOS, IR and
CGR based λ_E
requirements
as function of $\overline{n}$

Break even:

CGR = ELOS: $\overline{n} = 0.35$

IR = ELOS: $\overline{n} = 0.8$

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IR criterion implications if ELOS based λ_E requirements are applied ?

$$\overline{n} = 1 \quad \overline{n} = 10 \quad \overline{n} = 100$$

Break-even of ELOS = IR is independent of population density
→ Same results for any area type, i.e. from Rural to Metro City Center

Schiphol rules regarding IR criterion:
- No new housing developments for locations where IR above threshold
- When IR 10x above threshold: Housing is stopped
- Waiver for remaining housing where IR is above threshold

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Individual risk map for $\overline{n} = 1$
under ELOS based
λ_E **requirement**
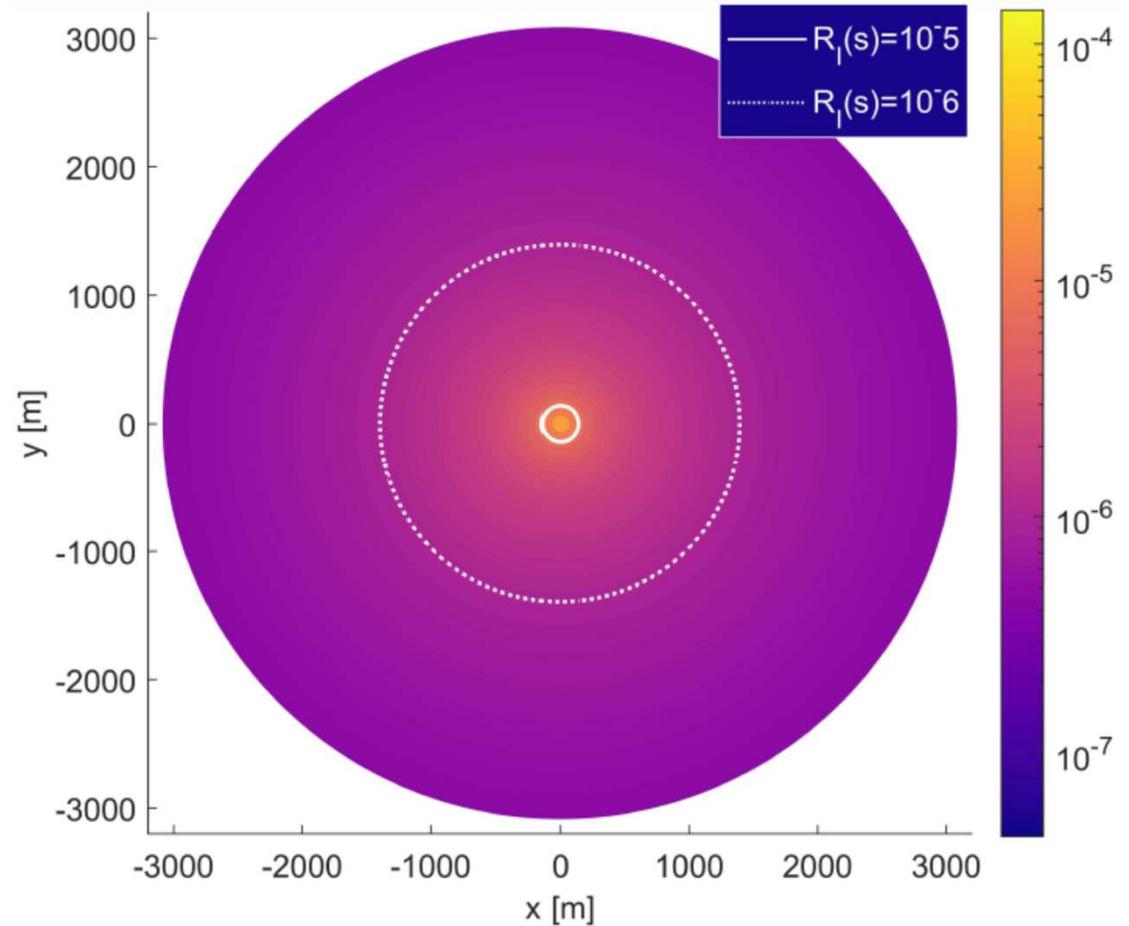
10x IR threshold at: **14 m**
→ 0.002% stop housing

IR threshold at: **139 m**
→ 0.2% receive waiver

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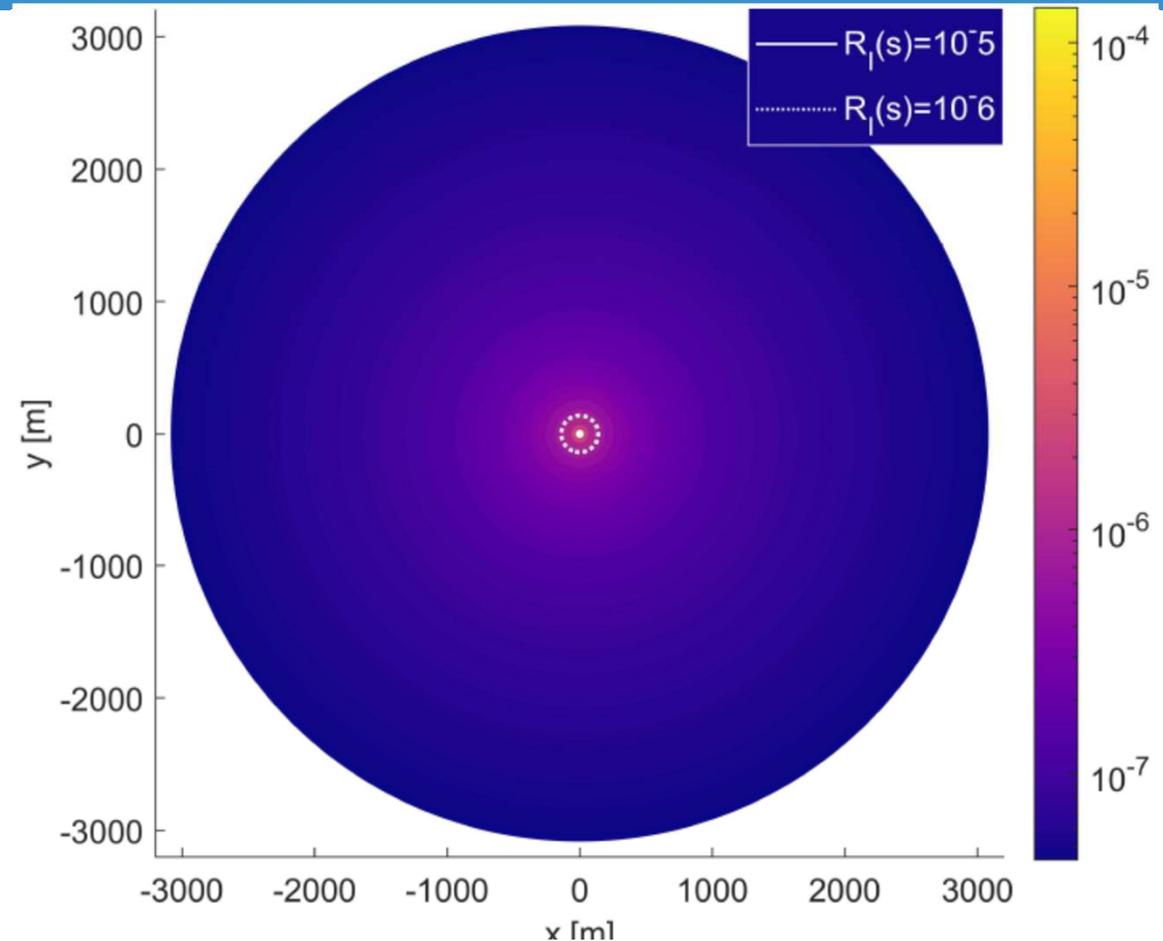
Individual risk map for $\overline{n} = 10$
under ELOS based
λ_E **requirement**
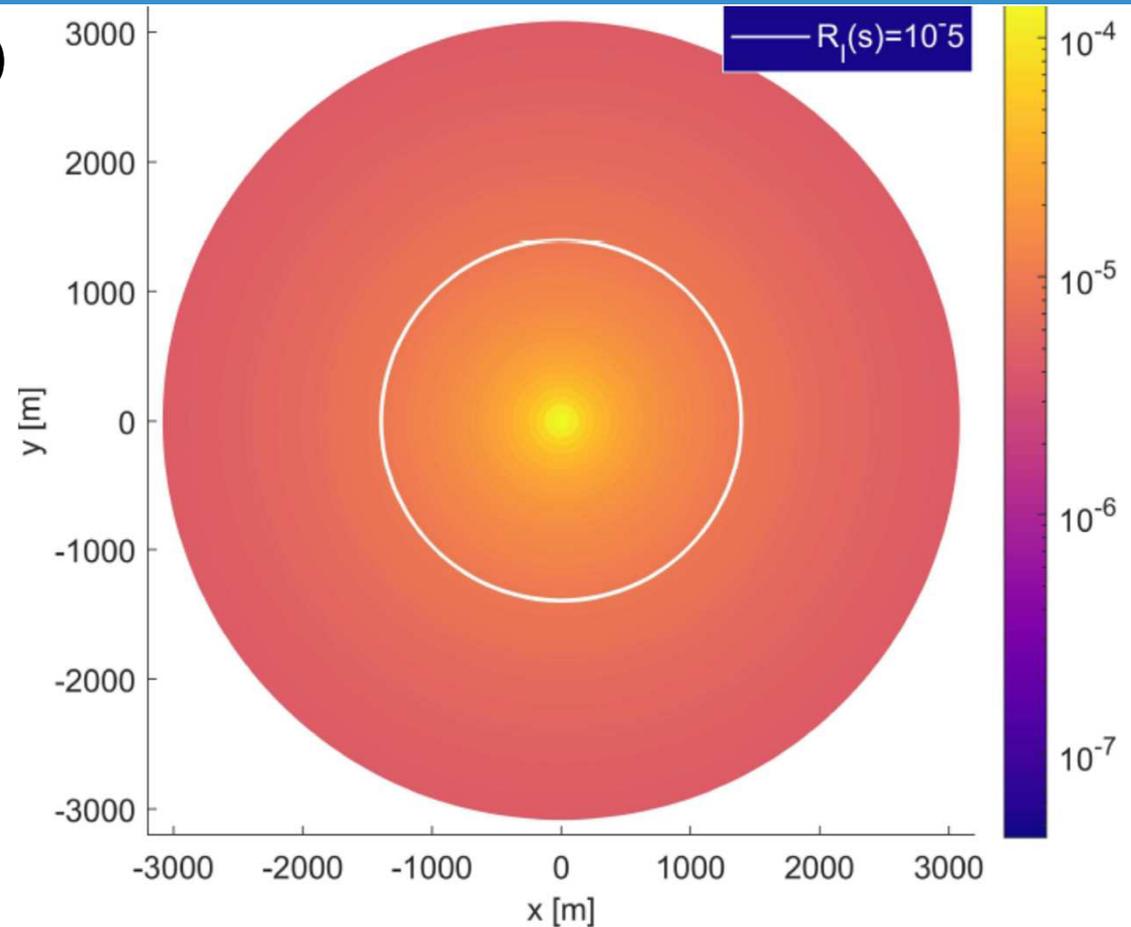
10x IR threshold at: **139 m**
→ 0.2% stop housing

IR threshold at: **1390 m**
→ 19.3% receive waiver

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Individual risk map for $\overline{n} = 100$
under ELOS based
λ_E **requirement**

10x IR threshold at: **1390 m**
→ 19.5% stop housing

IR threshold at: $\geq R$
→ 80.5% receive waiver

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- Existing Gap: Societal issues in areas with more potential customers:
  - Safety, Noise, Pollution, Privacy, Security and Cyber-security.

- So far UAS literature has addressed TPR from flight perspective, while airport and hazardous facilities consider all annual flights/operations.
  → Novel TPR indicators and thresholds for UAS operations:
  - Individual Risk (IR)
  - Collective Ground Risk (CGR)

- Two assessment methods:
  1. Monte Carlo simulation [Blom et al., RESS, 2021]
  2. Analytical characterization under simplifying assumptions (this paper)

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- Application of analytical approach to Last-mile Parcel delivery
  → ELOS, CGR and IR based λ_E requirements
- Evaluated examples:
  - Urban area: IR poses highest λ_E requirement if $\overline{n} > 0.8$
  - Metropolitan area: IR poses highest λ_E requirement if $\overline{n} > 0.8$
  - Metro City Center: CGR poses highest λ_E requirement if $\overline{n} > 0.35$
  - Under ELOS based λ_E and $\overline{n} = 10$ about 20% of area has too high IR
  - Under ELOS based λ_E and $\overline{n} = 100$ the full area has too high IR

→ For a commercial UAS parcel delivery service involving many annual flights, an ELOS based λ_E requirement does not comply with TPR regulation that has been developed for airports and hazardous facilities.

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Follow-on research
- To incorporate contribution to ground risk of mid-air collisions:
  - Two delivery UAS
  - Delivery UAS with other UAS or low flying GA.
- To extend the analytical approach to other type of UAS operations, e.g. flying taxis, medical drone services.
- To evaluate the TPR effects of advances in UAS support systems, e.g. risk based optimization of UAS flightpath.
- To improve TPR submodels, e.g.
  - Descend of UAS to crash location
  - Probability of Fatality
  - Shelter protection

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Thank you!

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