

Qualitative and quantitative risk assessment of urban airspace operations

Leonid Sedov¹, *Valentin Polishchuk*¹, Thibault Maury², Maria Ulloa³, Daria Lykova⁴

¹ Linköping University, Sweden

² ENAC, France

³ Universidad Politécnica de Madrid, Spain

⁴ Institut Le Rosey, Switzerland

Thanks:   TRAFIKVERKET VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

AïRMOUR



 11th SESAR Innovation Days



EASA regulations: Risk-based

Approval doesn't depend on

- what is done
inspection/photo/delivery
- how fun/important/...
- which country

Just prove risk is low

- nothing <
- nothing >

Specific Operations Risk Assessment
([SORA](#))

1.3(a): "The methodology .. aimed at evaluating the safety risks ... of any class, size or type of operation (including military, experimental, research and development and prototyping). It is particularly suited, but not limited to, 'specific' operations...."

SORA strengths

Scenario-based

- PDRA
- STS

Wide applicability

Qualitative ("pen&paper")

"uncomplicated and convenient means to qualitatively evaluate the safety risk associated with so-called specific category UAS operations"

[[Denny,Pai,Johnson@DASC'18](#)]

"SORA steps ... provide a risk assessment that does not require substantial knowledge of how to determine risks and necessary measures to mitigate them"

[[Cour-Harbo@ICUAS'18](#)]

SORA weaknesses

Scenario-based

Instead of generic scenarios,
could [dis]approve every
concrete, unique operation

Fun fact:

SORA's "Specific" = "Concrete" ?
not category

Qualitative ("pen&paper")

- "room for interpretation"
[[Cour-Harbo@ICUAS'18](#)]
(later slides)
- ELOS?
LOS (TLS) is quantitative
 $\text{EFR} < 10^{-6}$
(later slides)

Early voices to quantify SORA

GUTMA Annual conference:

"Defining how UTM services can best support the digitalization of airspace risk assessment (SORA)"

⊆

"the immediate hard challenges facing UTM"

Riga airspace assessment:

"However, the requirement to assign ground risk classes for UAS operation has prompted the conclusion that this process needs to be digitalised and automated to make significant resource savings for UAS operators and authorities, at least for determining the intrinsic UAS Ground Risk Class (GRC) "

2018:

UTM's ancient history

 11th SESAR Innovation Days



Recent chorus (CORUS on SORA -- later)

BUBBLES (SESAR ER4) D4.1:

"The SORA methodology will be guideline but the goal is to improve the qualitative methodology of SORA with a quantitative methodology, since that will allow to estimate a value for the RWC separation"

"proposing a quantitative risk analysis which enhances or replaces the qualitative model of SORA"

Fricke et al., ATMS'21

about their simulations:

"TUD [Dresden University of Technology] suggest integrating this type of agent simulation as air risk assessment in SORA"

SORA may be hard to fully automate...

SORA iGRC table: column ← span, energy

Intrinsic UAS ground risk class				
Max UAS characteristics dimension	1 m / approx. 3 ft	3 m / approx. 10 ft	8 m / approx. 25 ft	>8 m / approx. 25 ft
Typical kinetic energy expected	< 700 J (approx. 529 ft lb)	< 34 kJ (approx. 25 000 ft lb)	< 1 084 kJ (approx. 800 000 ft lb)	> 1 084 kJ (approx. 800 000 ft lb)
Operational scenarios				
VLOS/BVLOS over a controlled ground area ¹⁸	1	2	3	4
VLOS over a sparsely populated area	2	3	4	5
BVLOS over a sparsely populated area	3	4	5	6
VLOS over a populated area	4	5	6	8
BVLOS over a populated area	5	6	8	10
VLOS over an assembly of people	7			
BVLOS over an assembly of people	8			



11th SESAR Innovation Days



SORA iGRC table: column ← span, energy

Lorenzo Murzilli's in
[SORA video](#):
heated discussion in
JARUS WG6

- span, or
- energy ?

ending in:
span ~ energy

Intrinsic UAS ground risk class			
1 m / approx. 3 ft	3 m / approx. 10 ft	8 m / approx. 25 ft	>8 m / approx. 25 ft
< 700 J (approx. 529 ft lb)	< 34 kJ (approx. 25 000 ft lb)	< 1 084 kJ (approx. 800 000 ft lb)	> 1 084 kJ (approx. 800 000 ft lb)
1	2	3	4
2	3	4	5
3	4	5	6
4	5	6	8
5	6	8	10
7			
8			



11th SESAR Innovation Days



SORA iGRC table: column ← span, energy

Lorenzo Murzilli's in
[SORA video](#):
heated discussion in
JARUS WG6

- span, or
- energy ?

ending in:
span ~ energy

Intrinsic UAS ground risk class	
1 m / approx. 3 ft	3 m / approx. 10 ft
< 700 J (approx. 529 ft lb)	< 34 kJ (approx. 25 000 ft lb)
1	2
2	3
3	4
4	5
5	6
7	
8	

∃ drones with

- span>1m
- energy<700J

SORA iGRC table: column ← span, energy

"If there is a mismatch between the maximum UAS characteristic dimension and the typical kinetic energy expected, the applicant should provide substantiation for the chosen column."

Intrinsic UAS ground risk class	
1 m / approx. 3 ft	3 m / approx. 10 ft
< 700 J (approx. 529 ft lb)	< 34 kJ (approx. 25 000 ft lb)
1	2
2	3
3	4
4	5
5	6
7	
8	

∃ drones with

- span>1m
- energy<700J

SORA iGRC table: column ← span, energy

"If there is a mismatch between the maximum UAS characteristic dimension and the typical kinetic energy expected, the applicant should provide substantiation for the chosen column."

Intrinsic UAS ground risk class	
1 m / approx. 3 ft	3 m / approx. 10 ft
< 700 J (approx. 529 ft lb)	< 34 kJ (approx. 25 000 ft lb)
1	2
2	3
3	4
4	5
5	6
7	
8	

∃ drones with

- span > 1m
- energy < 700J

Substantiation...???

May be hard to
automate this



I'm not a robot



SORA

May be hard to automate
in general

Many examples

- described in literature
- found in SORA

Strength: Qualitative → flexibility

At the same time ...

Allows quantitative methods
which may be easier to

- digitize
- automate
- computerize
- formalize
- model mathematically with rigor
- numerically calculate
- have algorithms for
- use data-driven approaches for



11th SESAR Innovation Days



SORA

Trivia question (🍷) :

#hits when searching for

- "qualitative"
- "quantitative"

SORA

Trivia question (🍷) :

#hits when searching for

- "qualitative" 29
- "quantitative" 9

#4: warning!

"The SAIL is not quantitative"

When was the last time
someone did
arithmetic operations
with Roman numerals?

##1--3, 8, 9: qual ↔ quant interplay!

- ...use either qualitative .. or quantitative.. , or consider both
- ...quantitative ... allows to reduce quantitative ... used to validate ...
- assessment ... qualitative ... augmented with quantitative ...
- translate ... quantitative ... into qualitative ...

SORA

To finish with qual/quant in SORA
##5--7: explanation!

C.3.1 SORA qualitative vs quantitative approach

... assessment is qualitative... Where possible, ... will use quantitative data.. The SORA approach in general provides a balance between qualitative and quantitative approaches...

So, SORA isn't purely qual
Does/may $\exists$ purely qual
risk assessment method?
Philosophical Q for
after wine @SIDs dinner

Meanwhile, go2 quant method
Also based on

- Air risk
- Ground risk

Air risk quant methodology

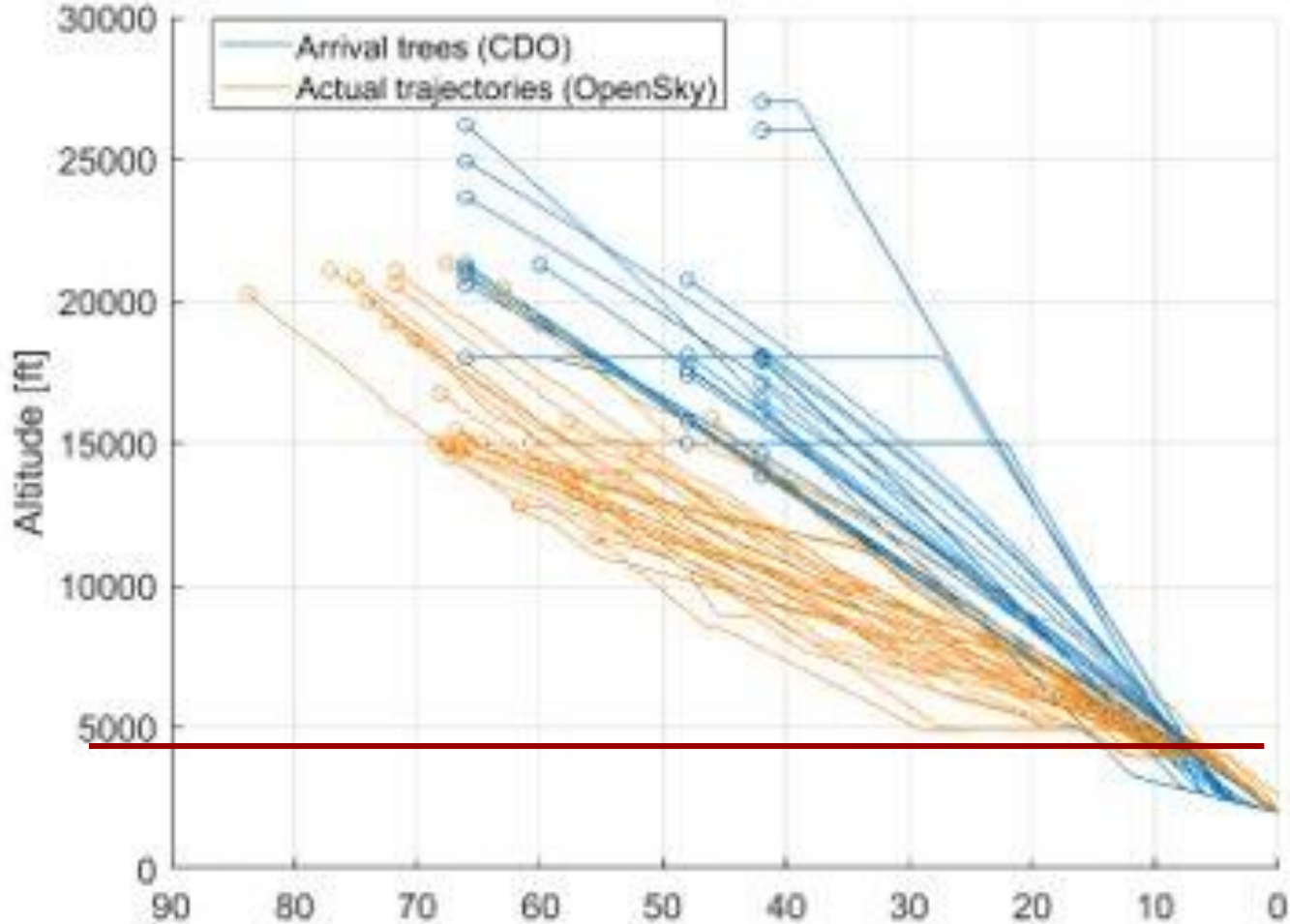
- [Weibel, Hansman. ATIO 2004]
- [Arctic Science RPAS Operator's Handbook](#)
- Zhang, Xuejun, et al. "Safety assessment and risk estimation for unmanned aerial vehicles operating in national airspace system." Journal of Advanced Transportation 2018 (2018)
- la Cour-Harbo, Schiøler. "Probability of Low-Altitude Midair Collision Between General Aviation and Unmanned Aircraft." Risk Analysis 39.11 (2019)
- Usach, Villa, Gallego. "Trajectory-based probabilistic risk model for UAS operations." Risk Assessment in Air Traffic Management. IntechOpen, 2020

Instantiation

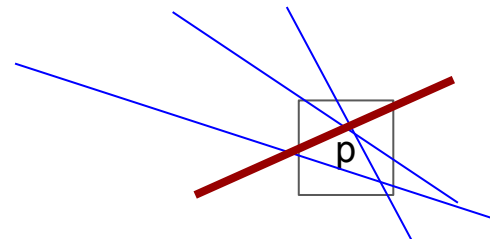
Stockholm

- TMA
 - GA, balloons, ...
- Hospital
 - EMS ops

ADS-B
altitude



Processing



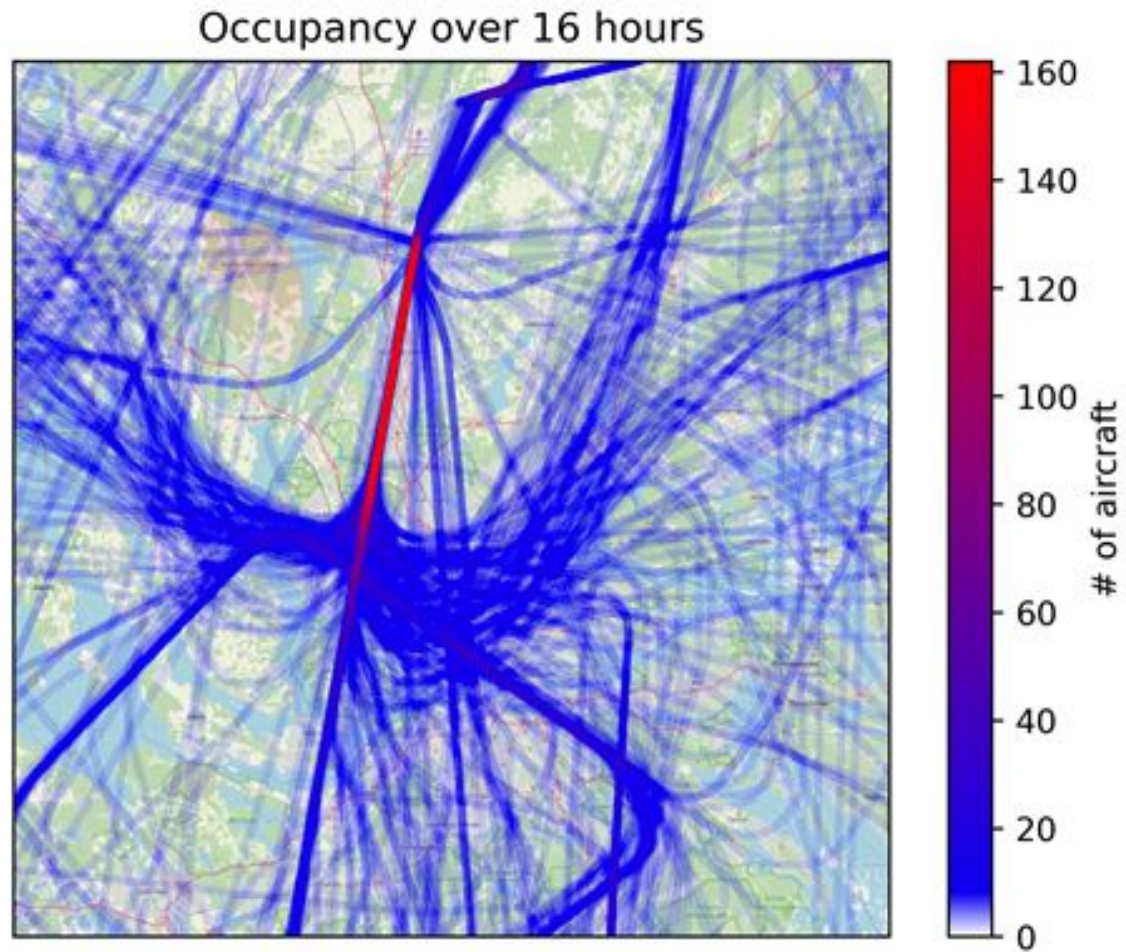
$\forall$ pixel p in ROI: $n_p = \#$ of **a/c flying through** p (or within 300m of p)
during time horizon $T=24\text{hrs}$ or 12hrs (or whatever you choose)

$E[\# \text{ a/c in } p / \text{ unit time}]$ (a/c traffic intensity) $= n_p / T$ (eg $12\text{a/c} / 12\text{hrs} = 1\text{a/c} / \text{hr}$)
assume const, but can do fine-grained (morning, day, night, specific hrs...)

$t =$ time for **our vehicle** to pass through a pixel
assume const, depending on speed but can do fine-grained (speed profile)

$E[\# \text{ conflicts with a/c in } p] = n_p t / T$
makes sense: we run (not walk) crossing a highway to min $\#$ of cars hitting us

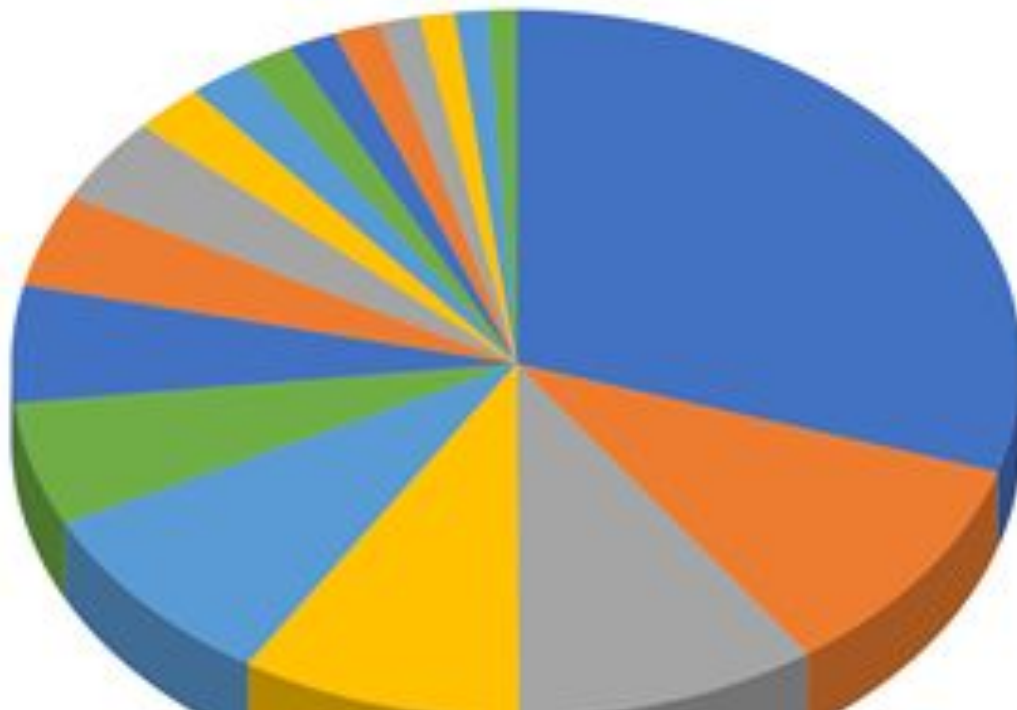
E[conflicts with a/c]



11th SESAR Innovation Days

Fleet types

Type of aircraft	Number
BOEING 737-800	33335
AIRBUS A-320neo	11444
BOEING 737-700	10798
BOMBARDIER Reg	10012
AIRBUS A-320	9626
ATR ATR-72-600	6294
BOEING 737-600	5963
AIRBUS A-321	4761
AIRBUS A-319	4321
SAAB 340	2512
AIRBUS A-330-300	2228
BOMBARDIER Das	1800
EMBRAER E190-E2	1679
FOKKER F50	1643
BOEING 787-8 Dre	1447
BOEING 757-200	1255
BRITISH AEROSPA	1170
BOEING 767-300E	1027



- BOEING 737-800
- AIRBUS A-320neo
- BOEING 737-700
- BOMBARDIER Regional Jet CRJ-900
- AIRBUS A-320
- ATR ATR-72-600
- BOEING 737-600
- AIRBUS A-321
- AIRBUS A-319
- SAAB 340
- AIRBUS A-330-300
- BOMBARDIER Dash 8 Q400
- EMBRAER E190-E2
- FOKKER F50
- BOEING 787-8 Dreamliner
- BOEING 757-200

11th SESAR Innovation Days

EFR (Expected Fatality Rate)

NB: $p\{\text{collision}|\text{conflict}\} =$
 $p\{180\text{fatalities}|\text{collision}\} = 1$
[SORA] ANSP, operators?

$$E[\# \text{ conflicts with a/c along a path } P] = \sum_{p \text{ in } P} n_p t/T$$

time to fly $P = |P|t$ ($|P|$ = # of pixels through which P goes)

$$\begin{aligned} E[\text{conflict rate}] &= E[\# \text{ conflicts with a/c along a path } P] / \text{unit time} = \\ &= \sum_{p \text{ in } P} n_p t/T / \text{time to fly } P = 1/T \sum_{p \text{ in } P} n_p / |P| = \text{mean}(n_p)/T \end{aligned}$$

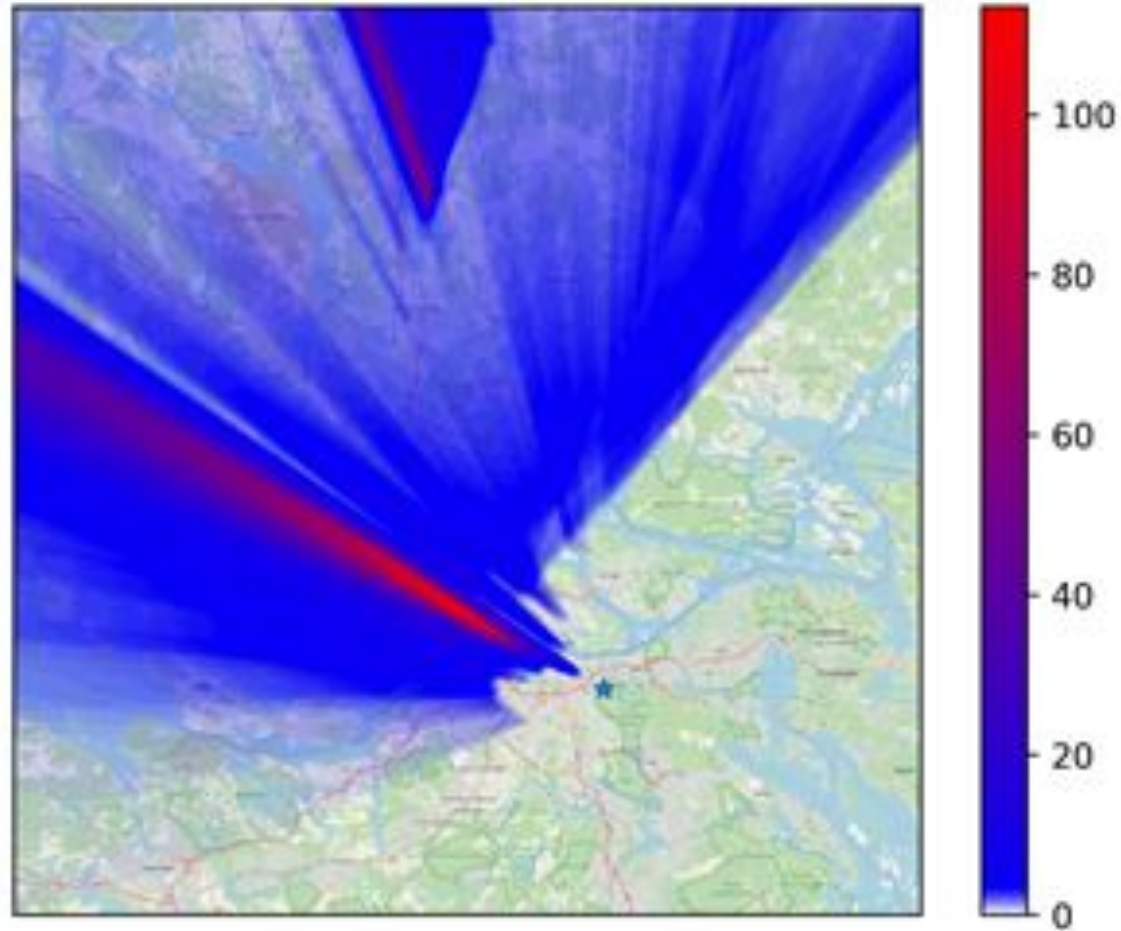
$$\text{EFR} = E[\text{conflict rate}] * E[\text{pax}] = \text{mean}(n_p)/T * 180$$

[[Usach, Villa, Gallego'20](#)]: "the most probable intruder aircraft when flying in controlled airspace is a short-to-medium-range airliner like a Boeing 737 or an Airbus A320 (two of the world's most successful commercial airliners), with an estimated capacity of 180 pax"

We're > fine-grained: count only where routes are, with local traffic intensity
(~~all of the controlled airspace~~)

EFR

0/1, b&w



11th SESAR Innovation Days



EFR Bromma

0/1, b&w

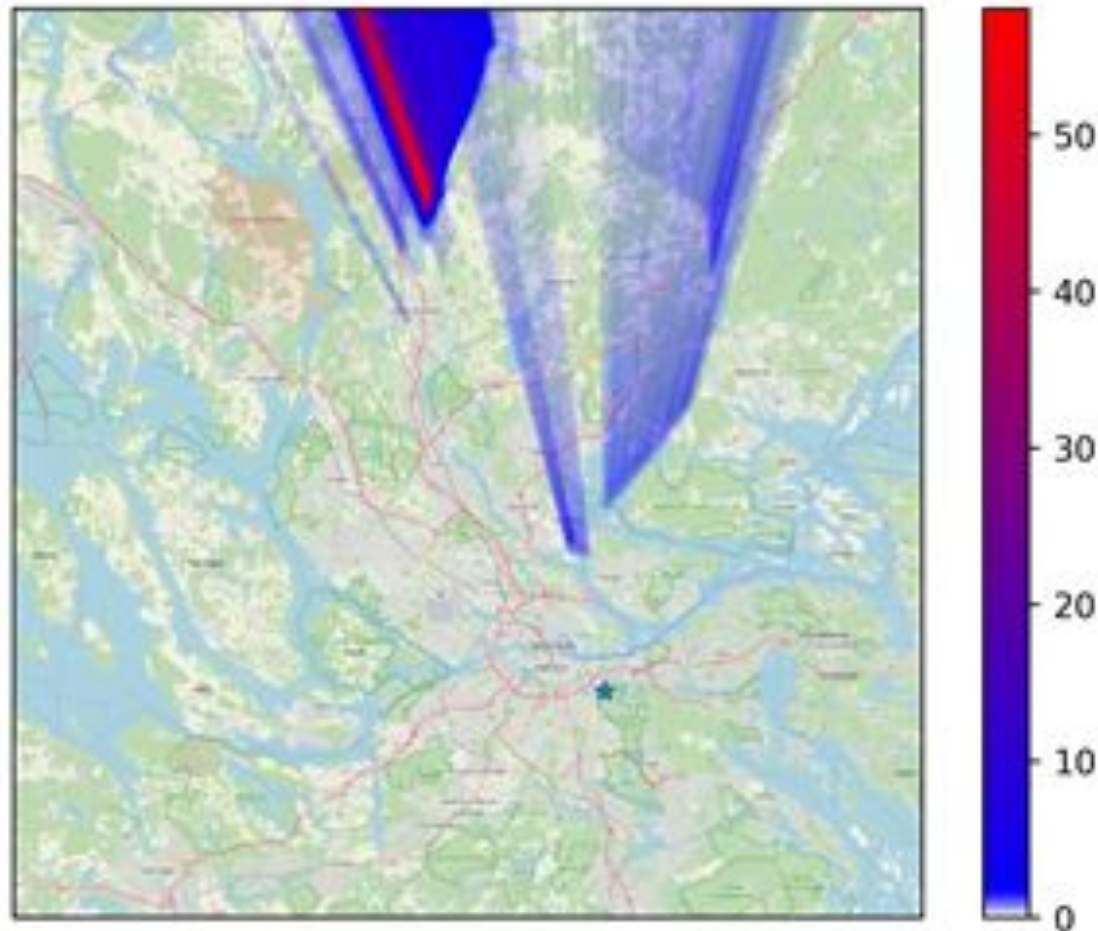
2öre from UAM POV to "to B or not to B (only A)"

hot topic in Sweden

B=Bromma ~~Boeing~~, A=Arlanda ~~Airbus~~

Conventional aviation vs U-space
(Reg 665, 666; AMC/GM pending)

- VI cent AD: In Rome,
Do as the Romans Do
- XXI cent AD: In U-space,
Do as the Drones Do

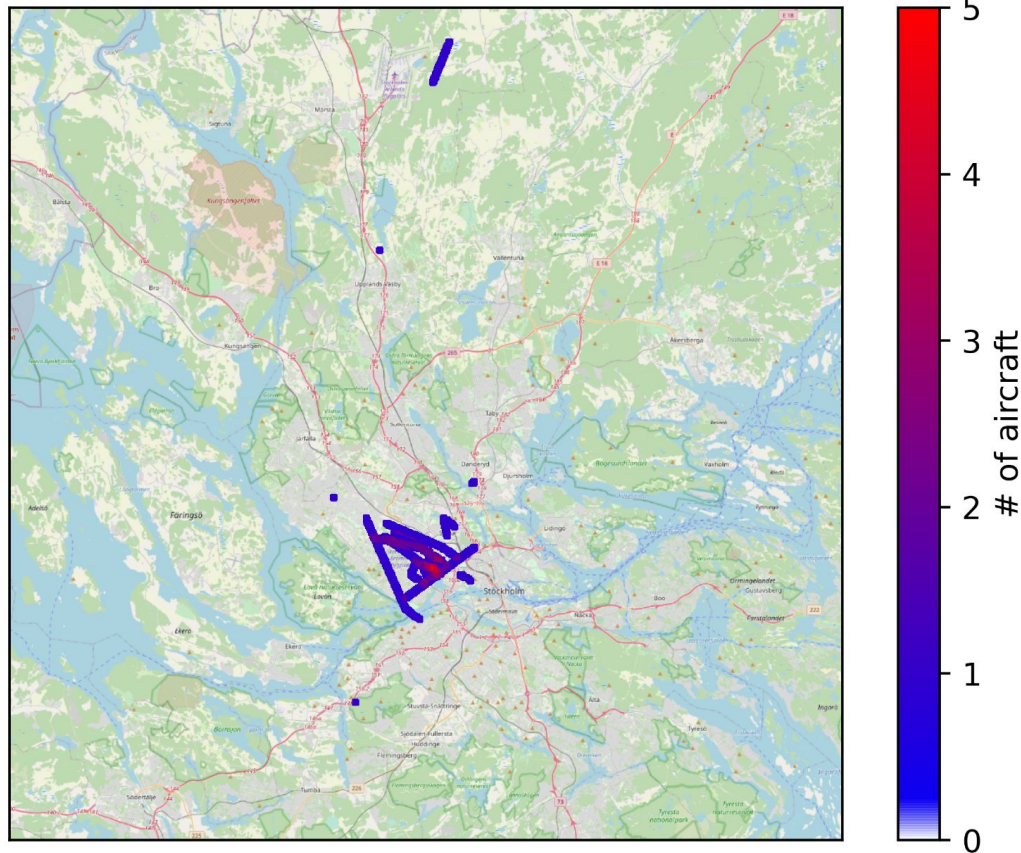


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 0-100m

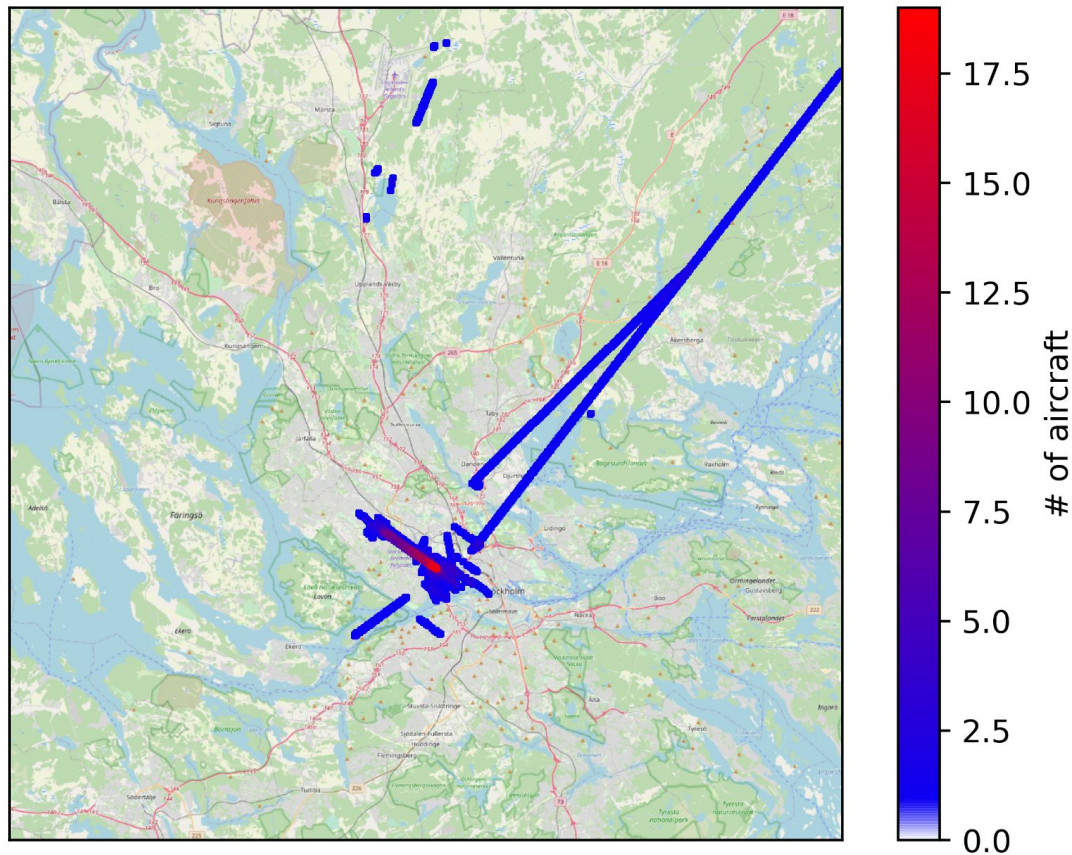


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 100-200m

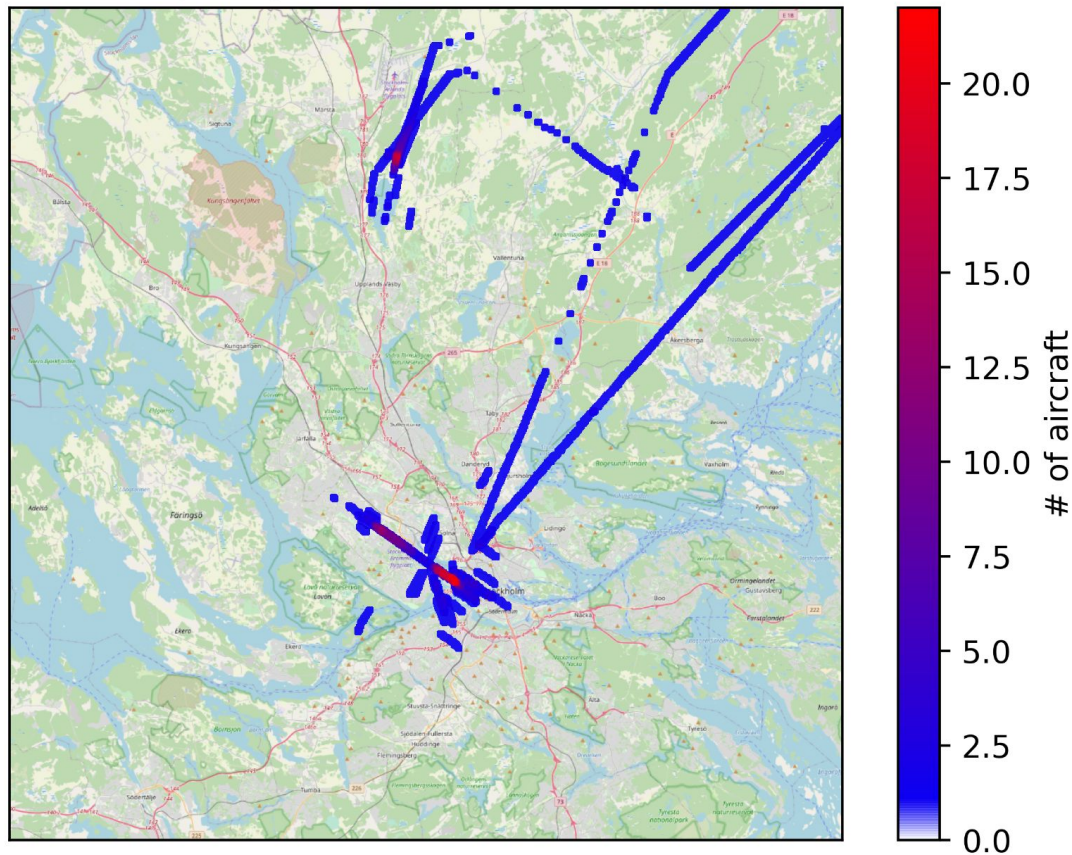


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 200-300m

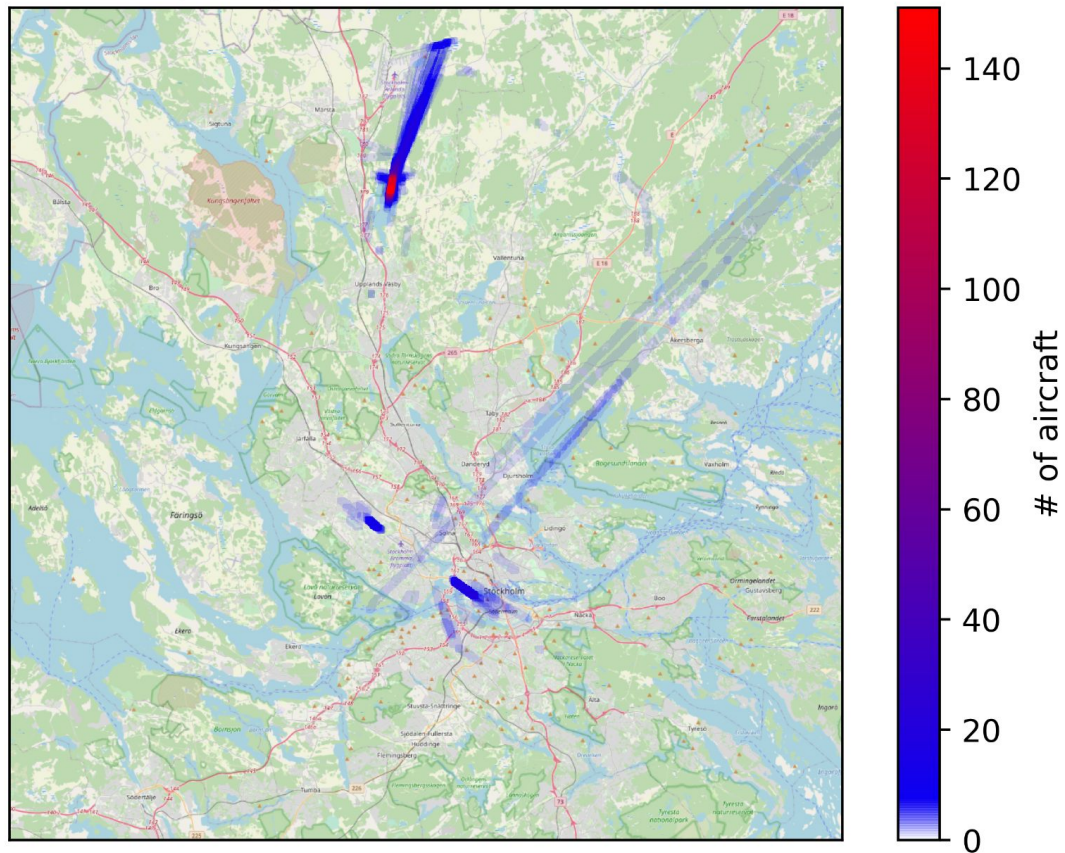


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 300-400m

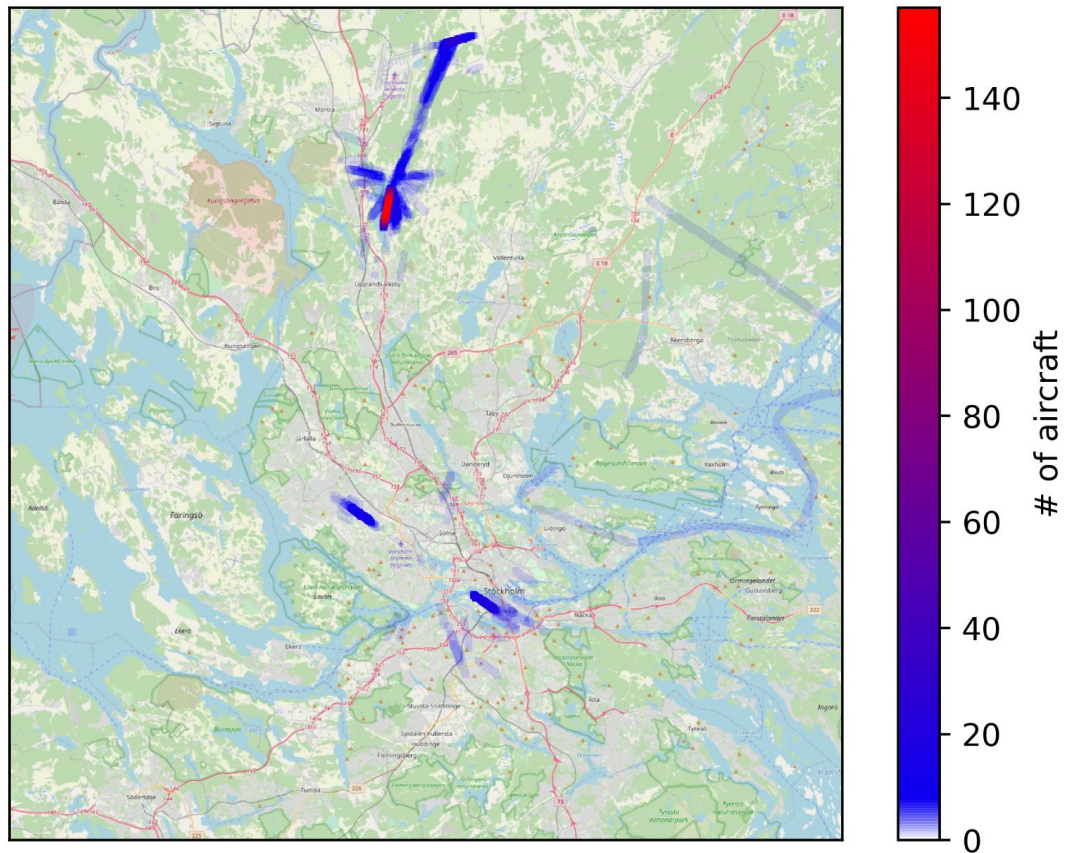


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 400-500m

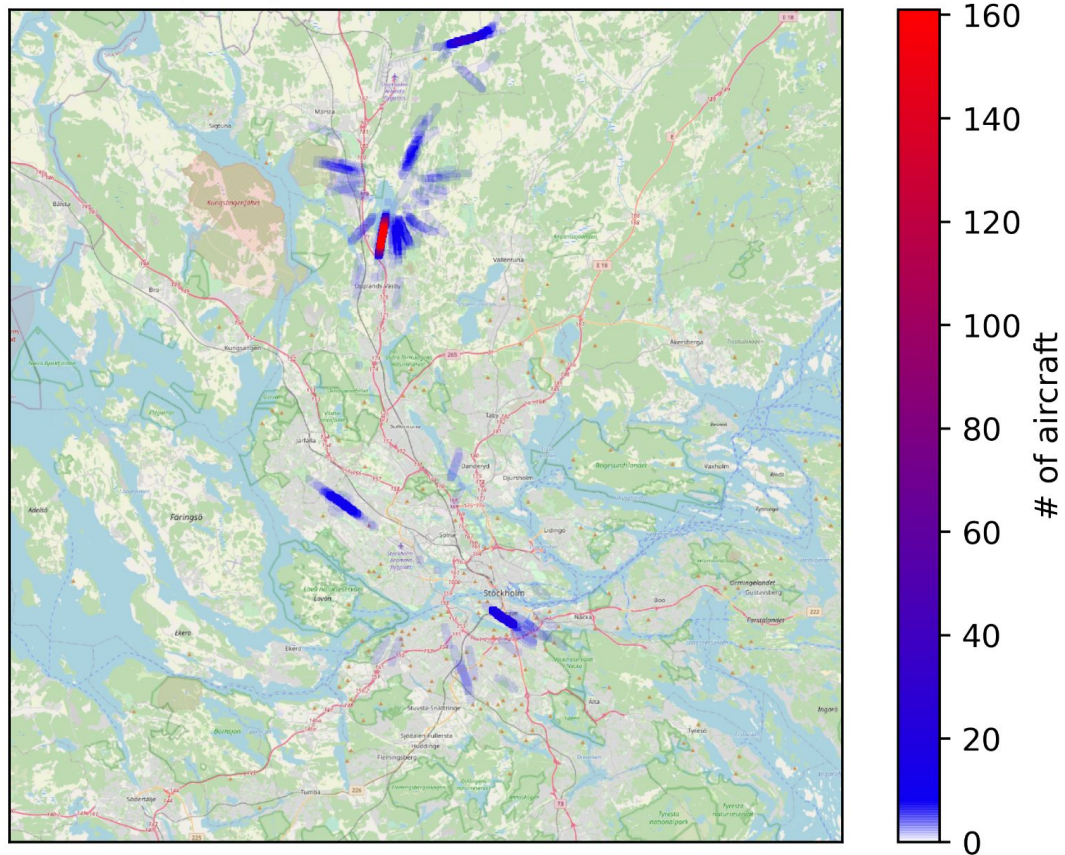


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 500-600m

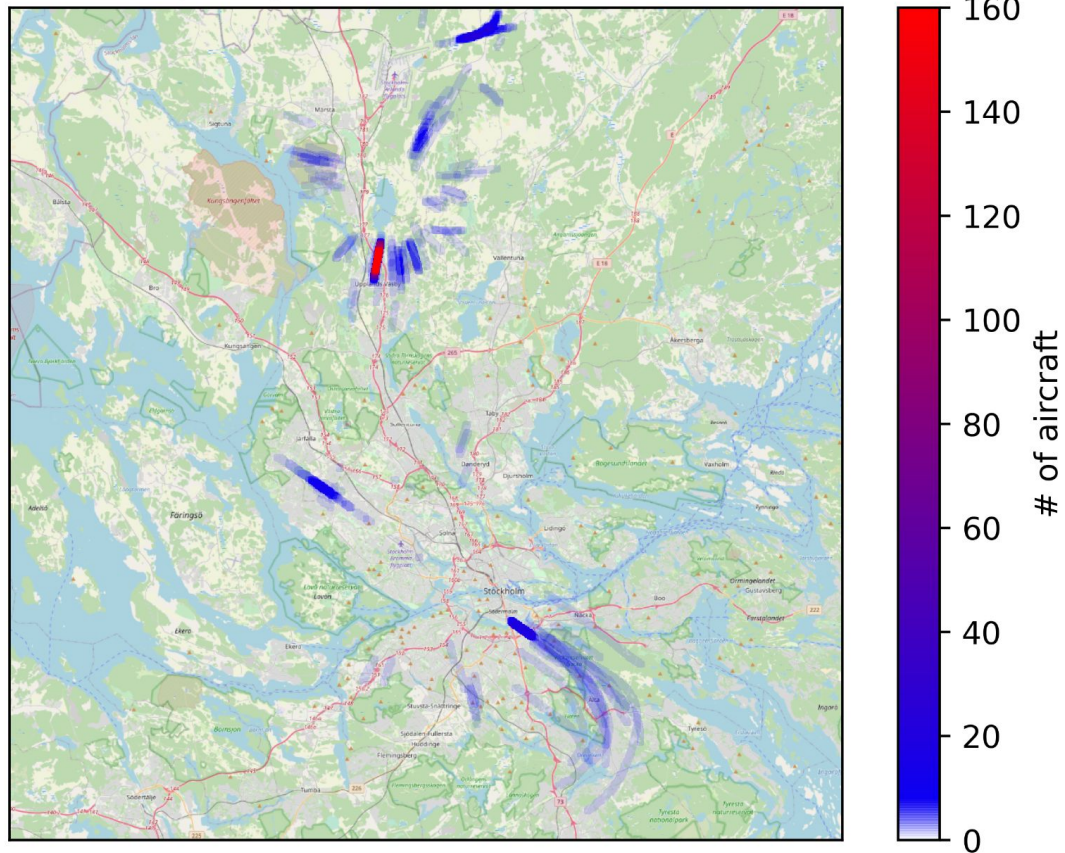


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 600-700m

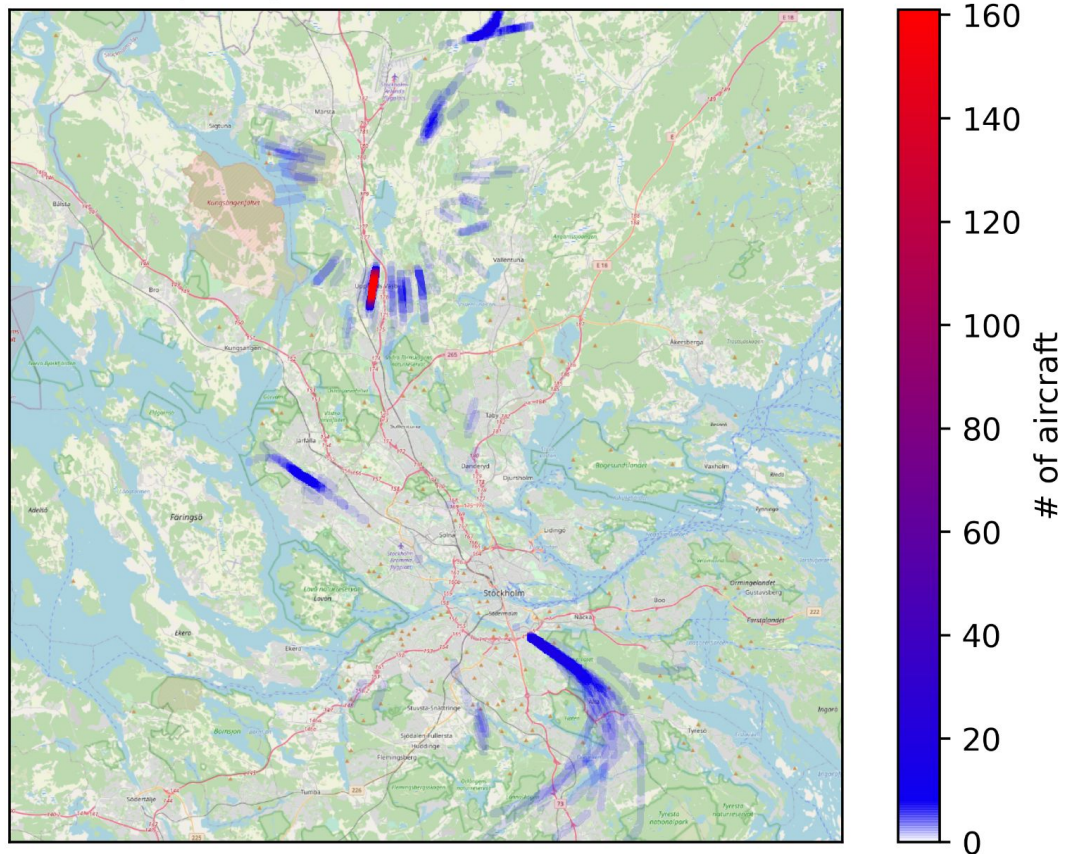


11th SESAR Innovation Days



E[conflicts with a/c]

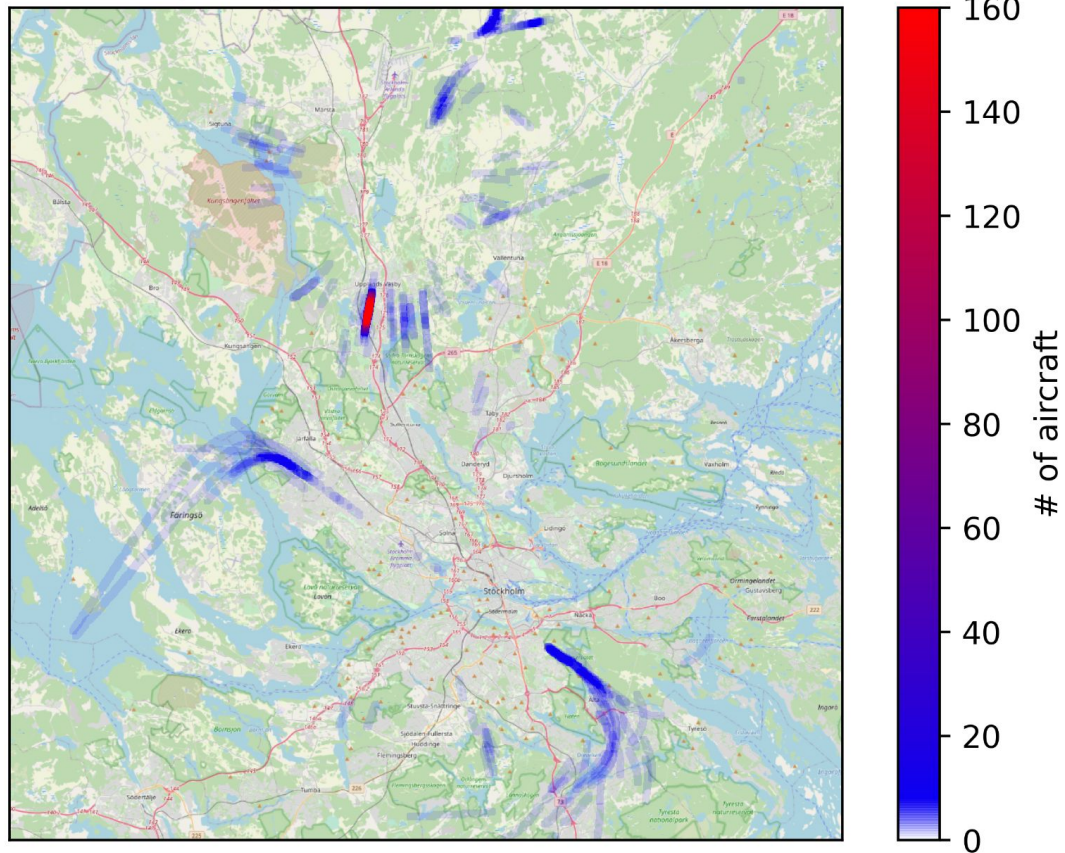
Occupancy over 16 hours 700-800m



11th SESAR Innovation Days

E[conflicts with a/c]

Occupancy over 16 hours 800-900m

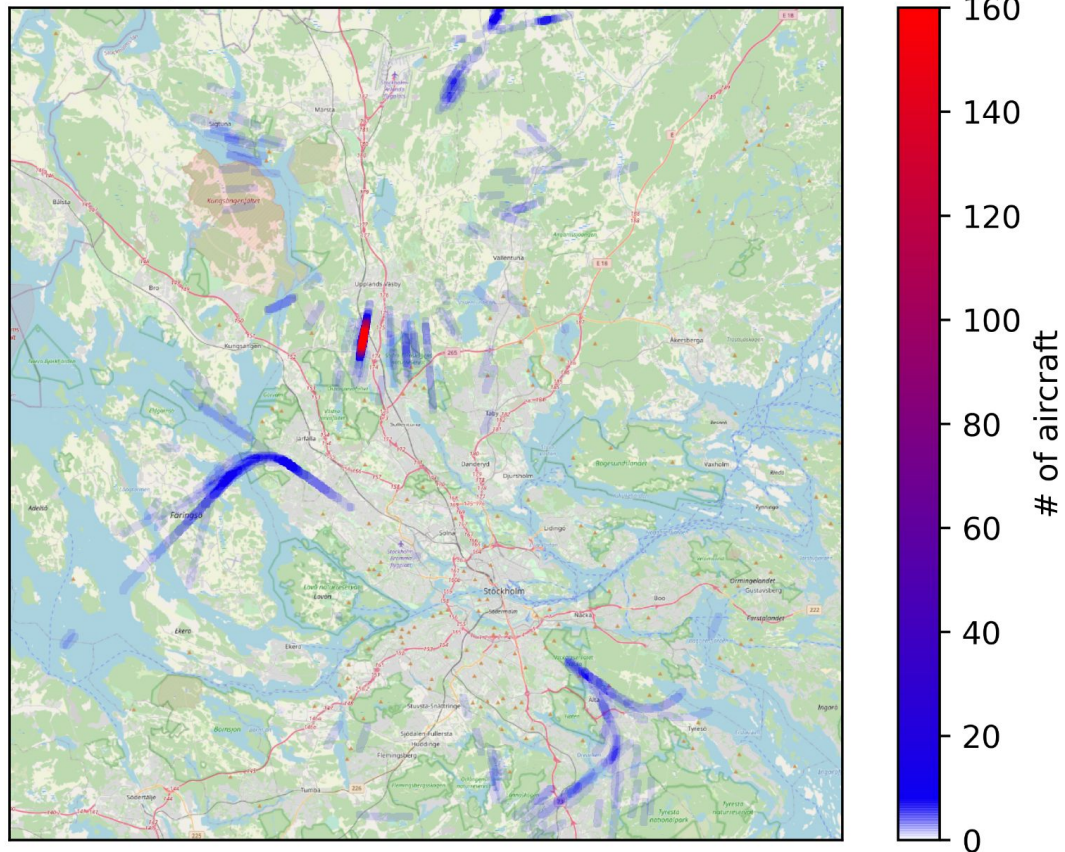


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 900-1000m

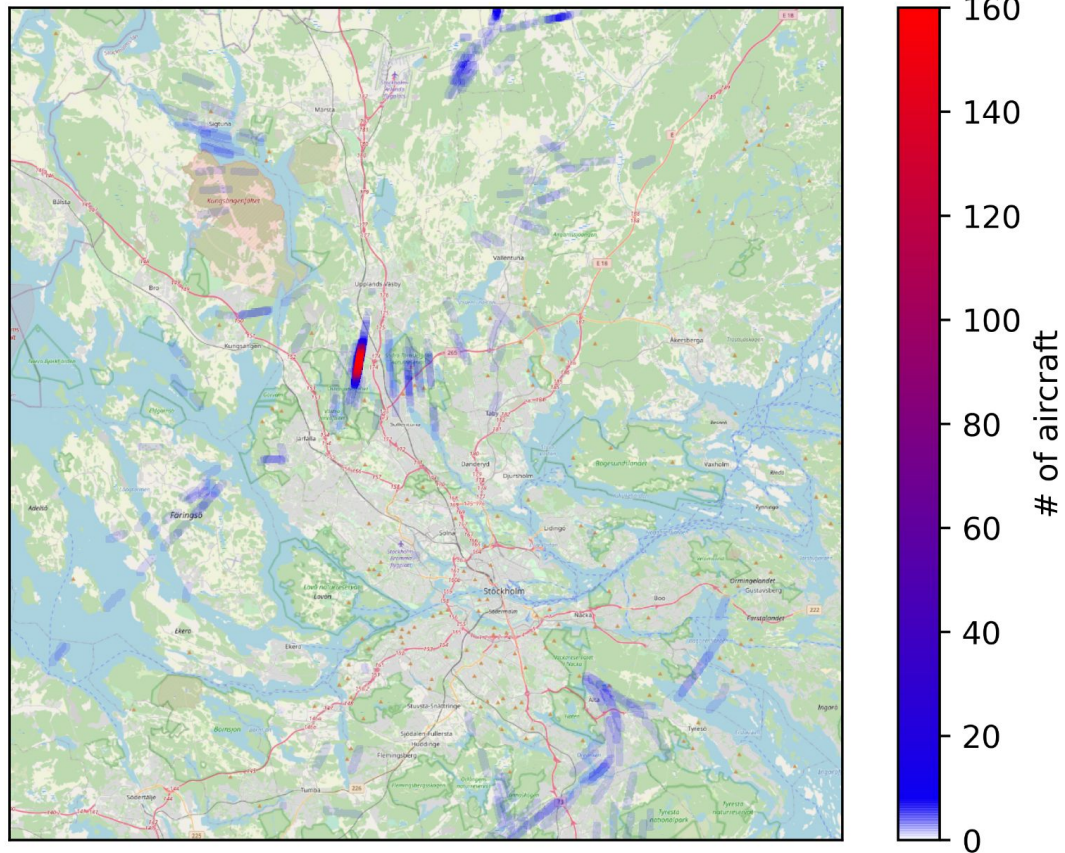


11th SESAR Innovation Days



E[conflicts with a/c]

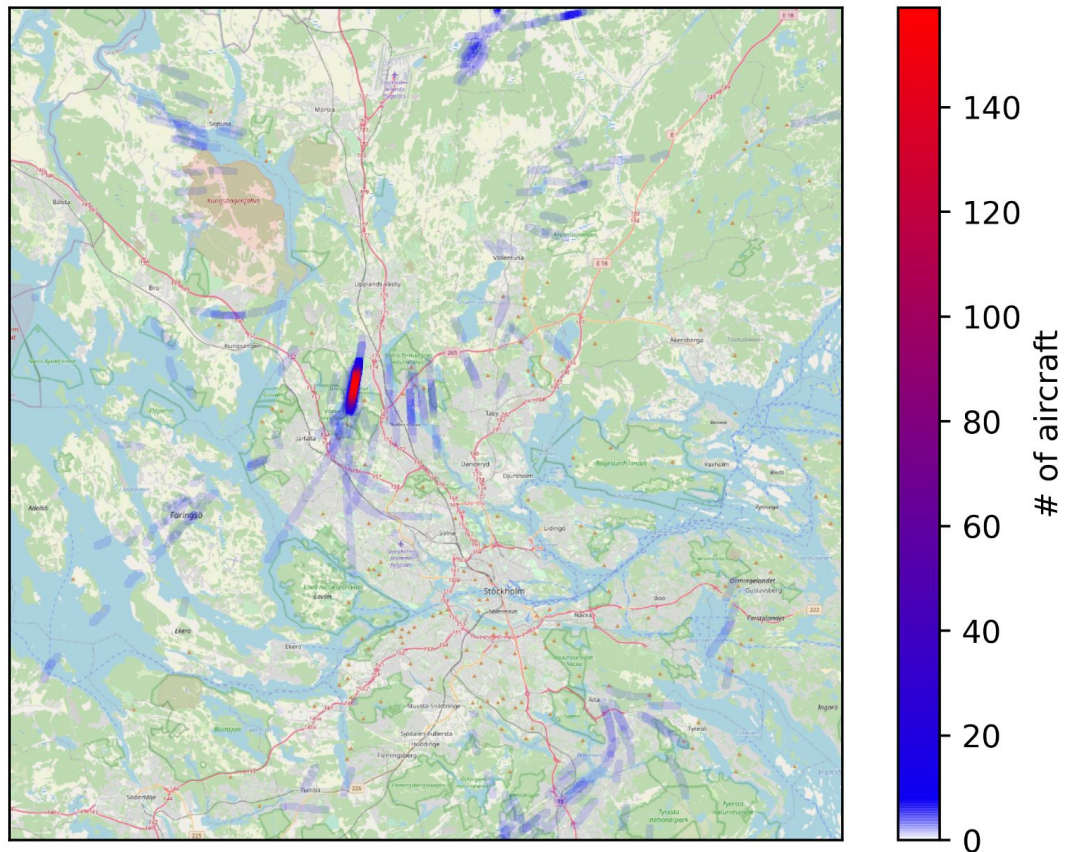
Occupancy over 16 hours 1000-1100m



11th SESAR Innovation Days

E[conflicts with a/c]

Occupancy over 16 hours 1100-1200m

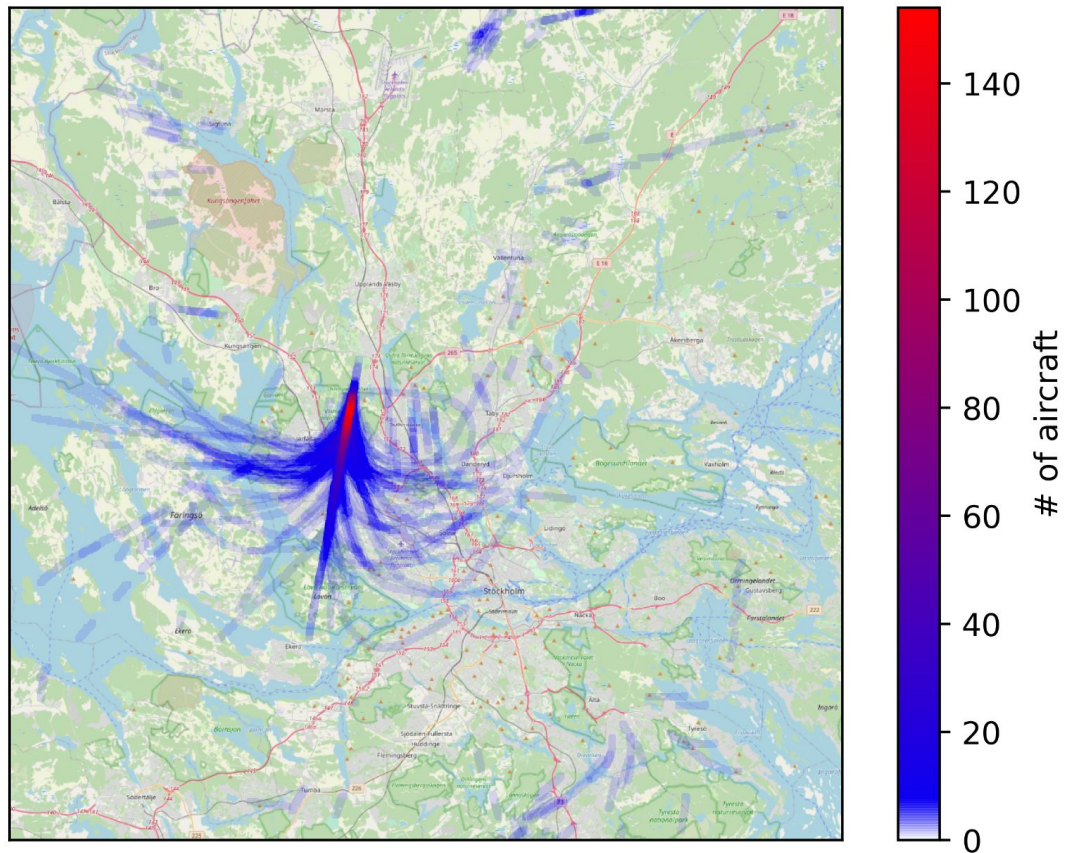


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 1200-1300m



11th SESAR Innovation Days

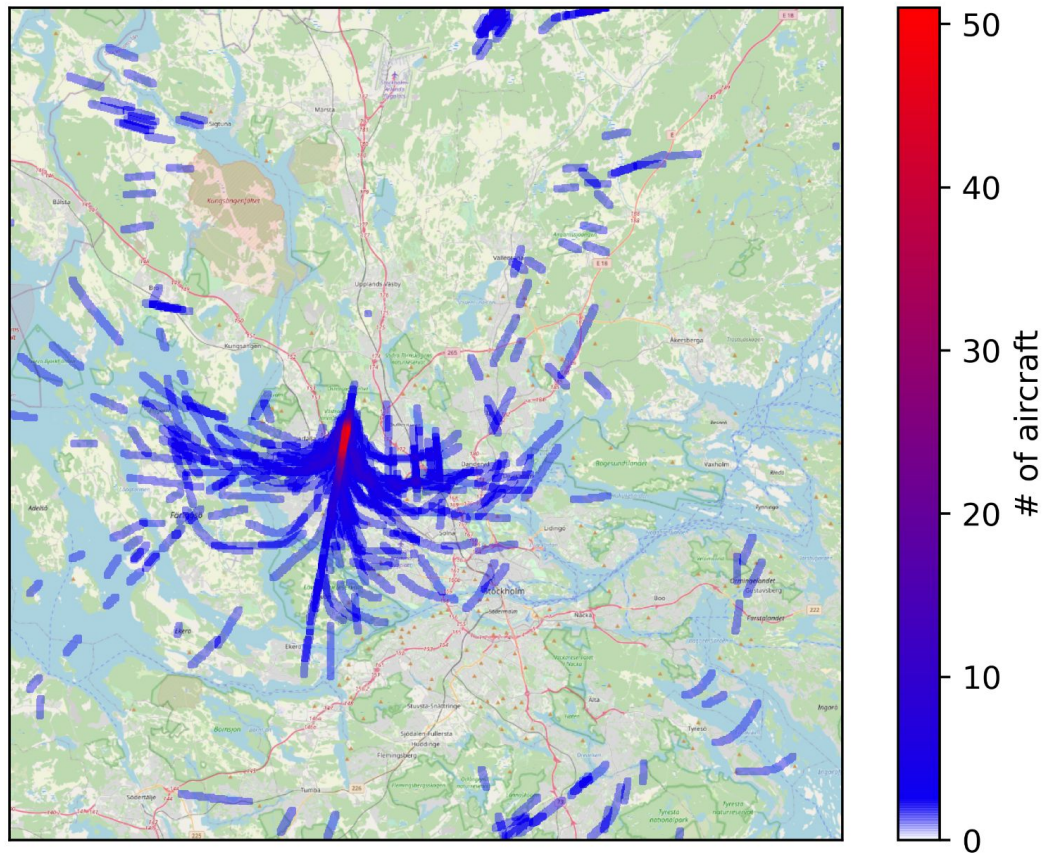


founding members



E[conflicts with a/c]

Occupancy over 16 hours 1300-1400m

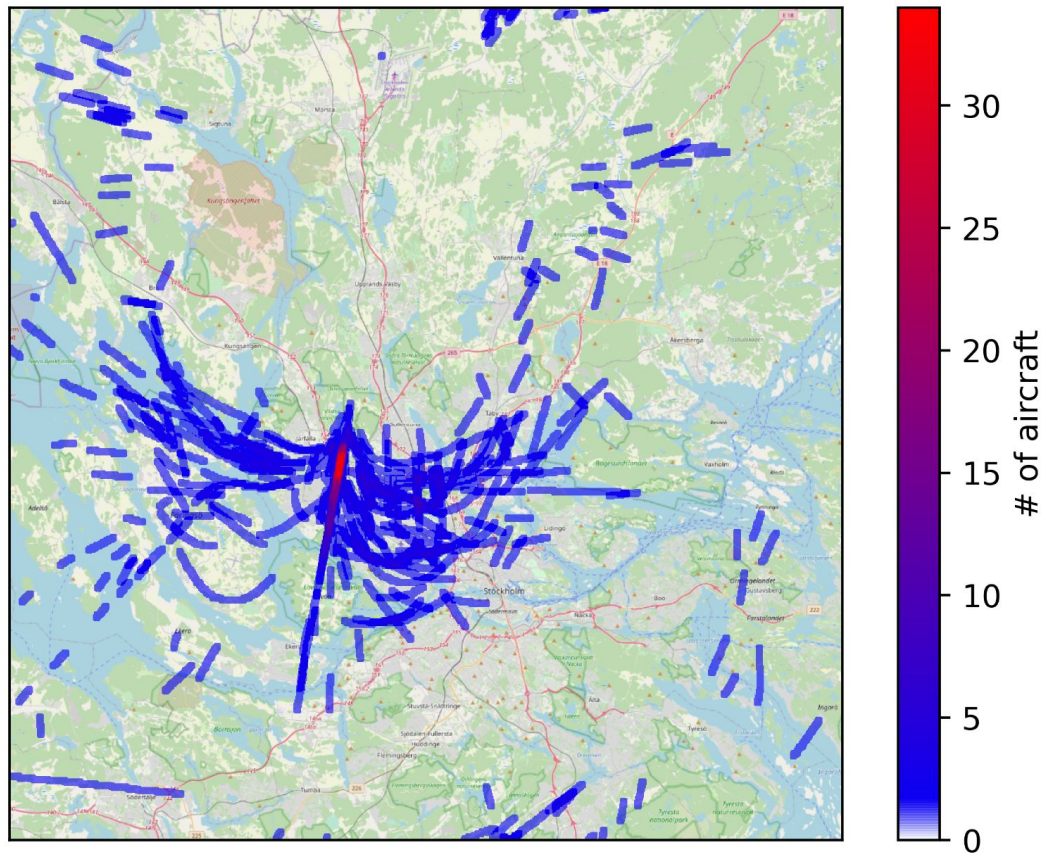


11th SESAR Innovation Days



E[conflicts with a/c]

Occupancy over 16 hours 1400-1500m



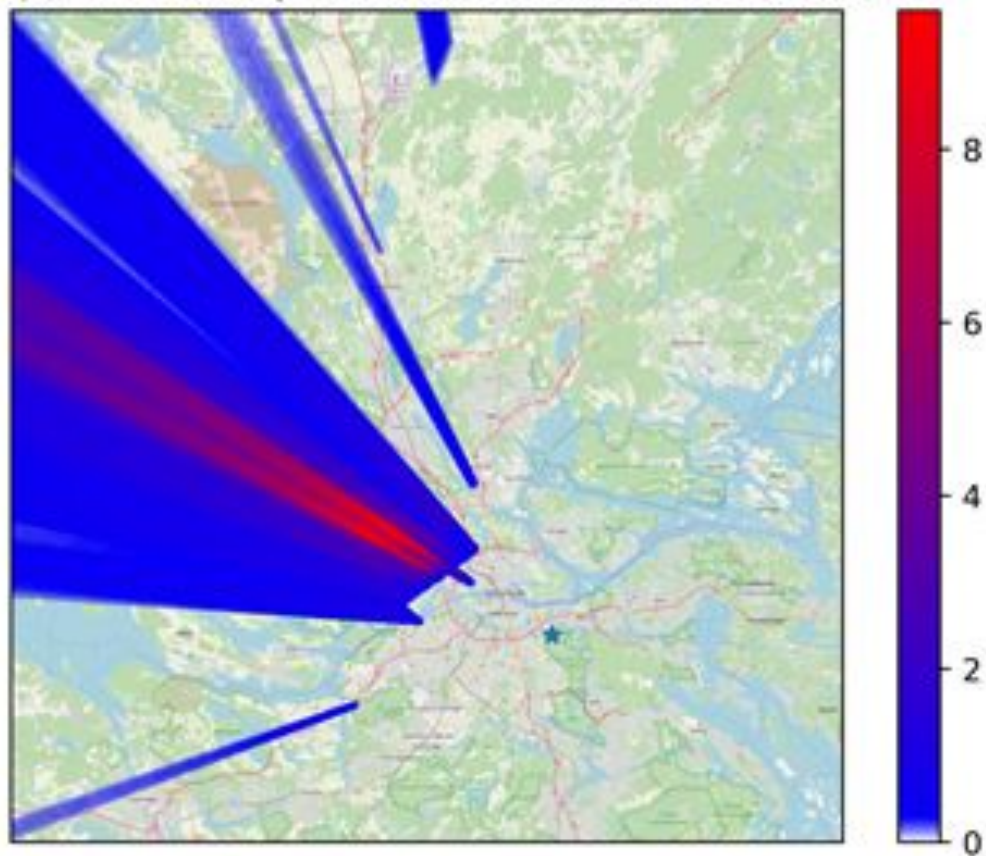
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 0m-100m)



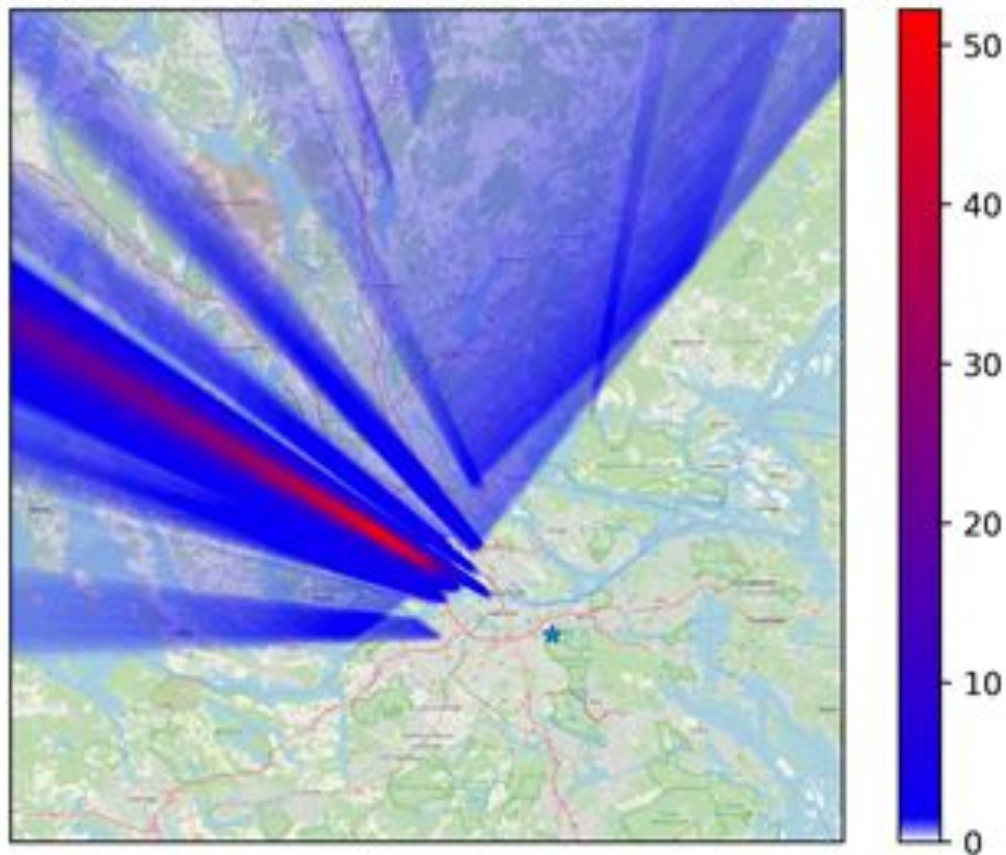
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 100m-200m)



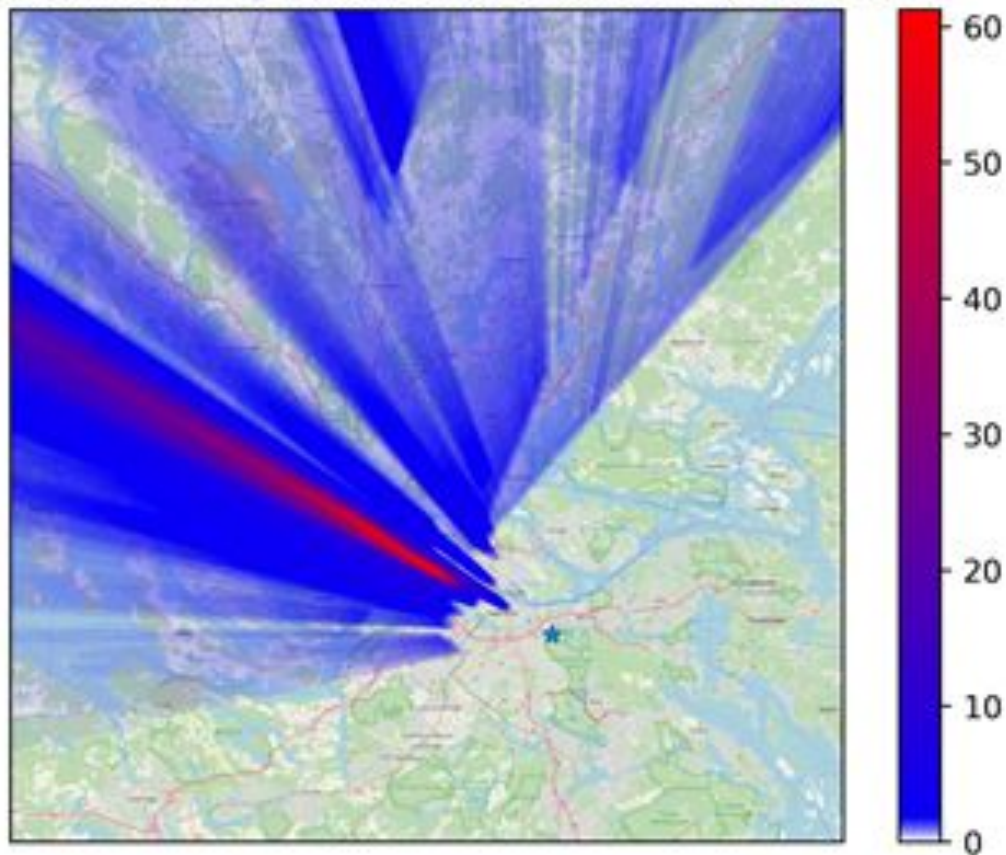
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 200m-300m)



11th SESAR Innovation Days



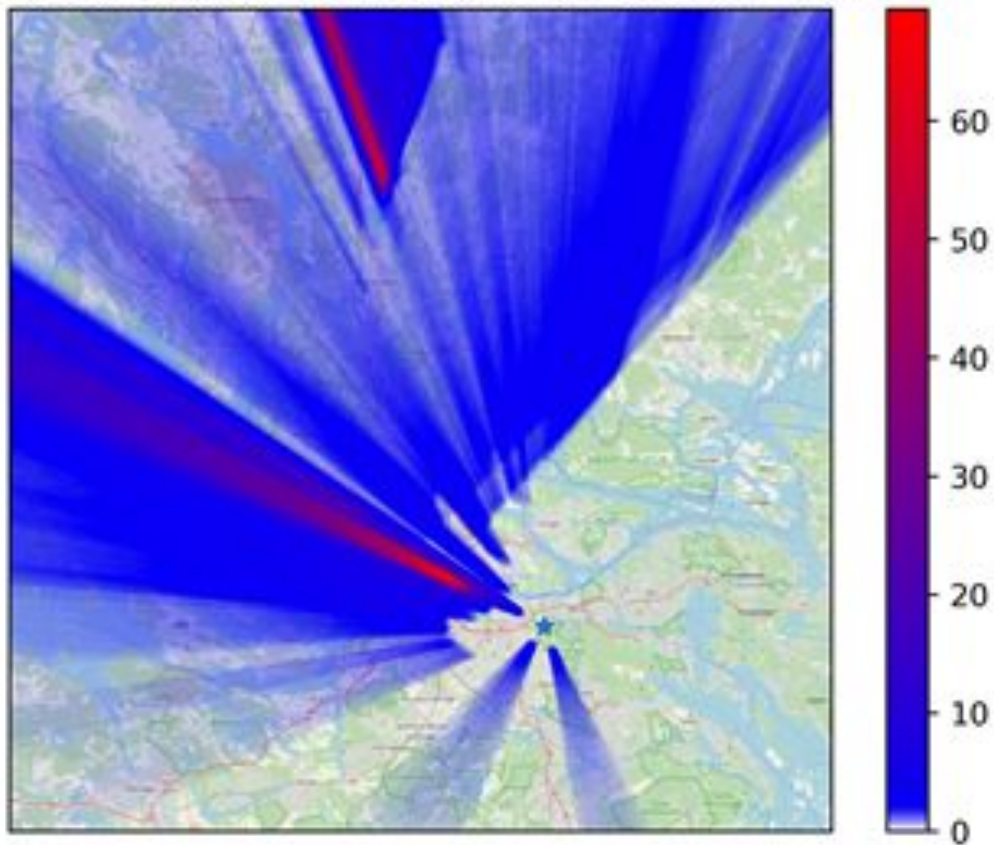
founding members



EFR

0/1, b&w

Expected Fatality Rate (altitude band 300m-400m)



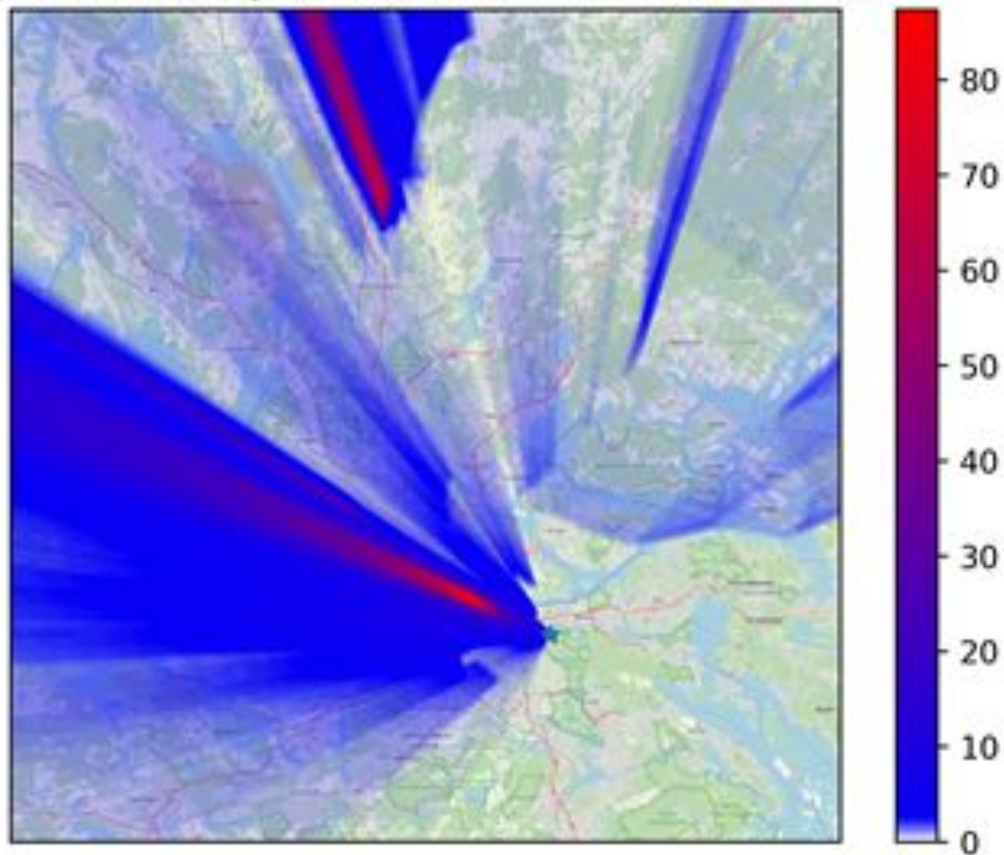
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 400m-500m)



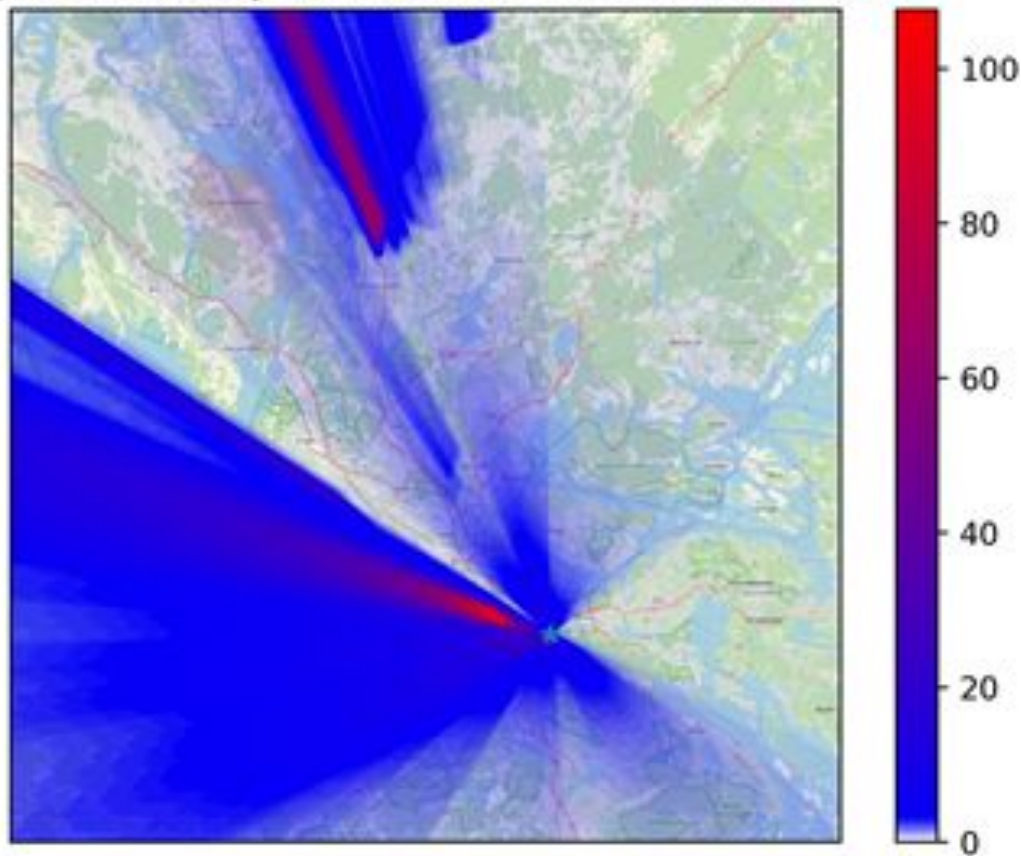
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 500m-600m)



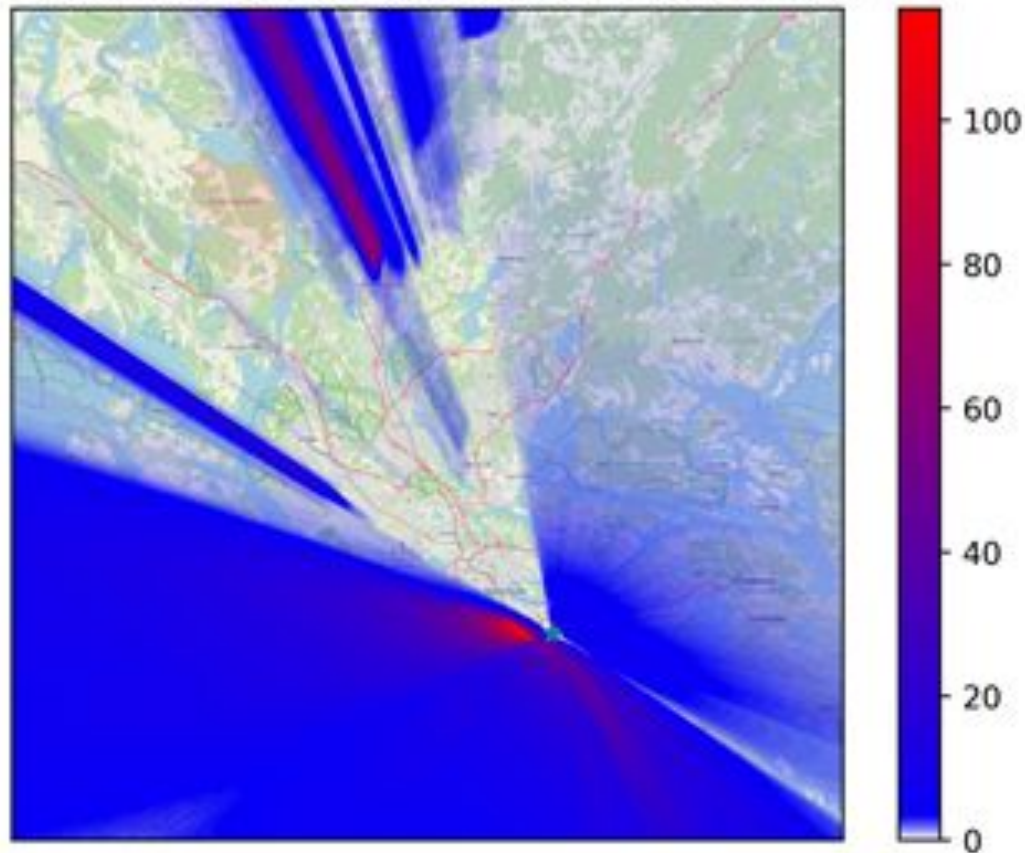
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 600m-700m)



11th SESAR Innovation Days



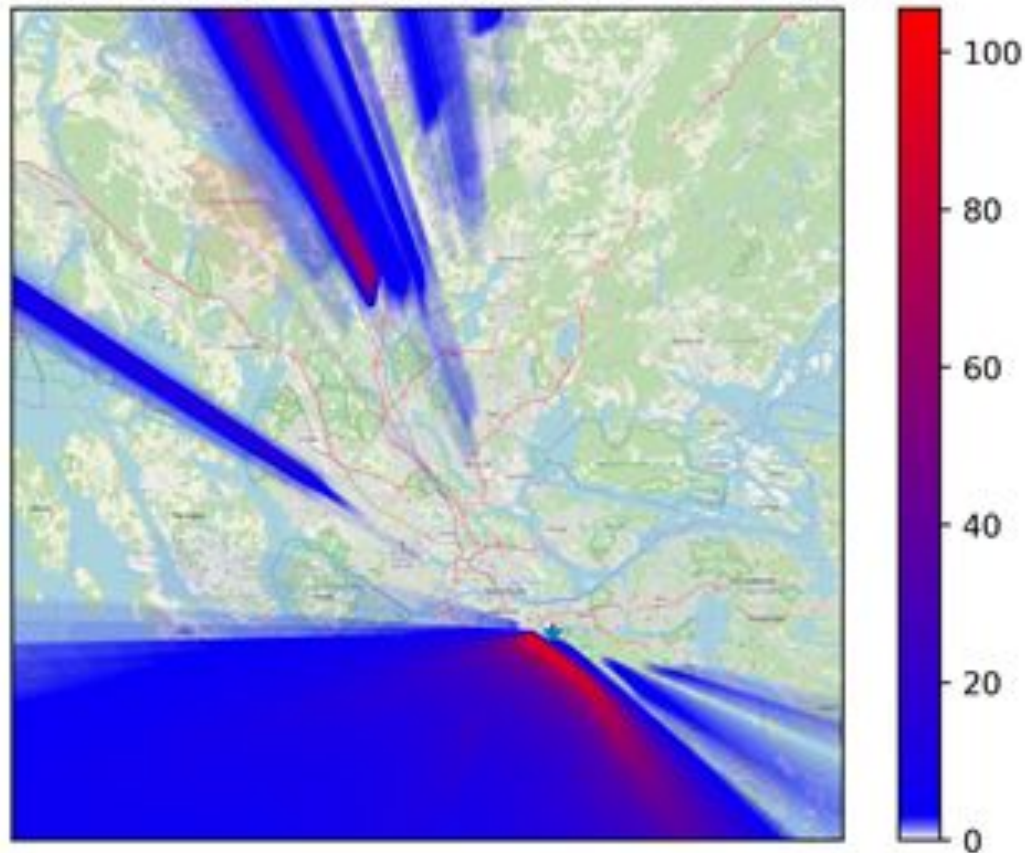
founding members



EFR

0/1, b&w

Expected Fatality Rate (altitude band 700m-800m)



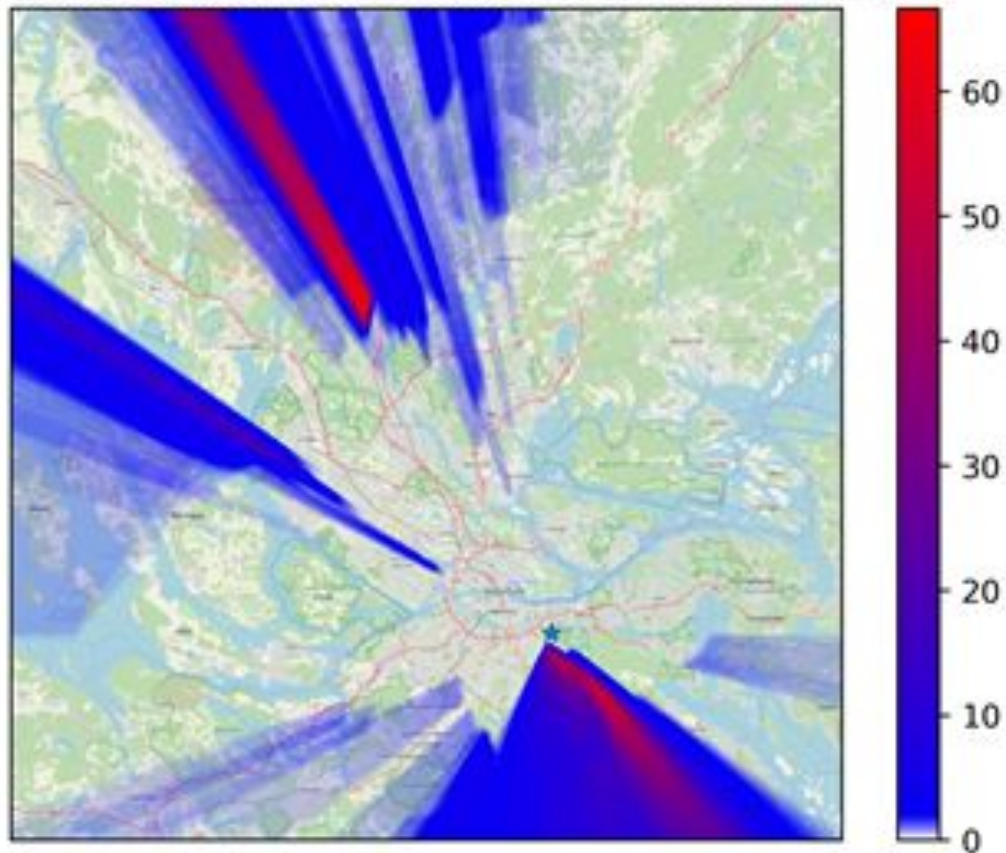
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 800m-900m)



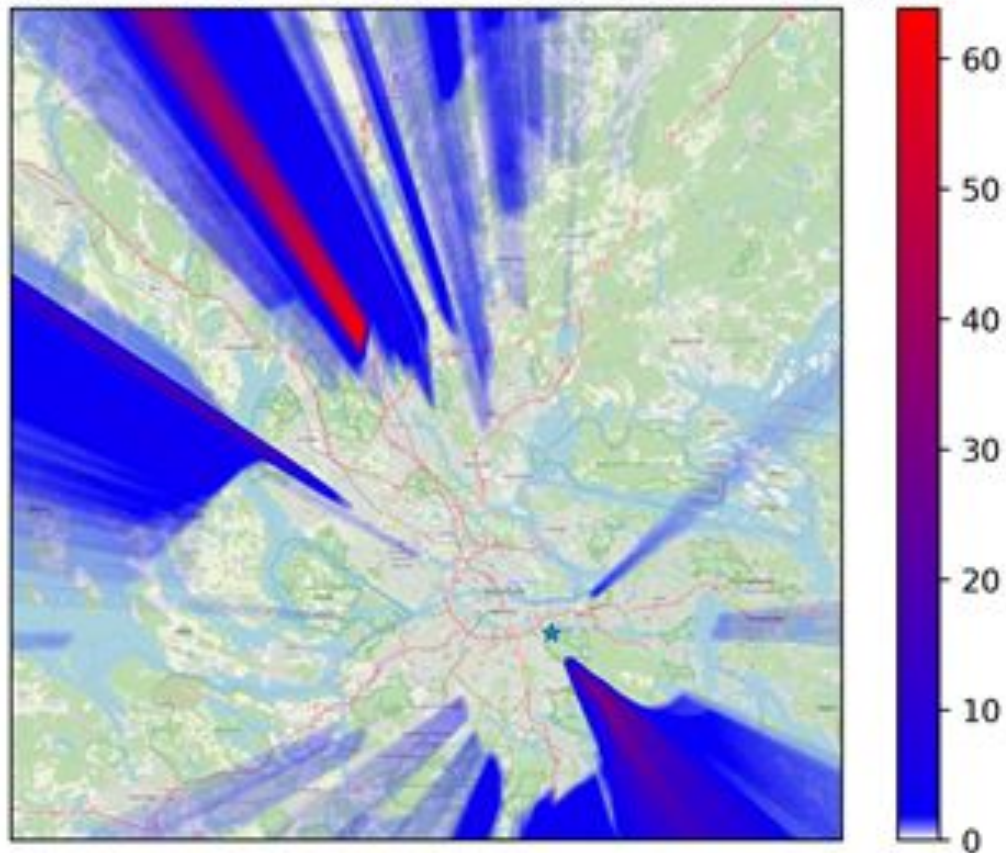
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 900m-1000m)



11th SESAR Innovation Days



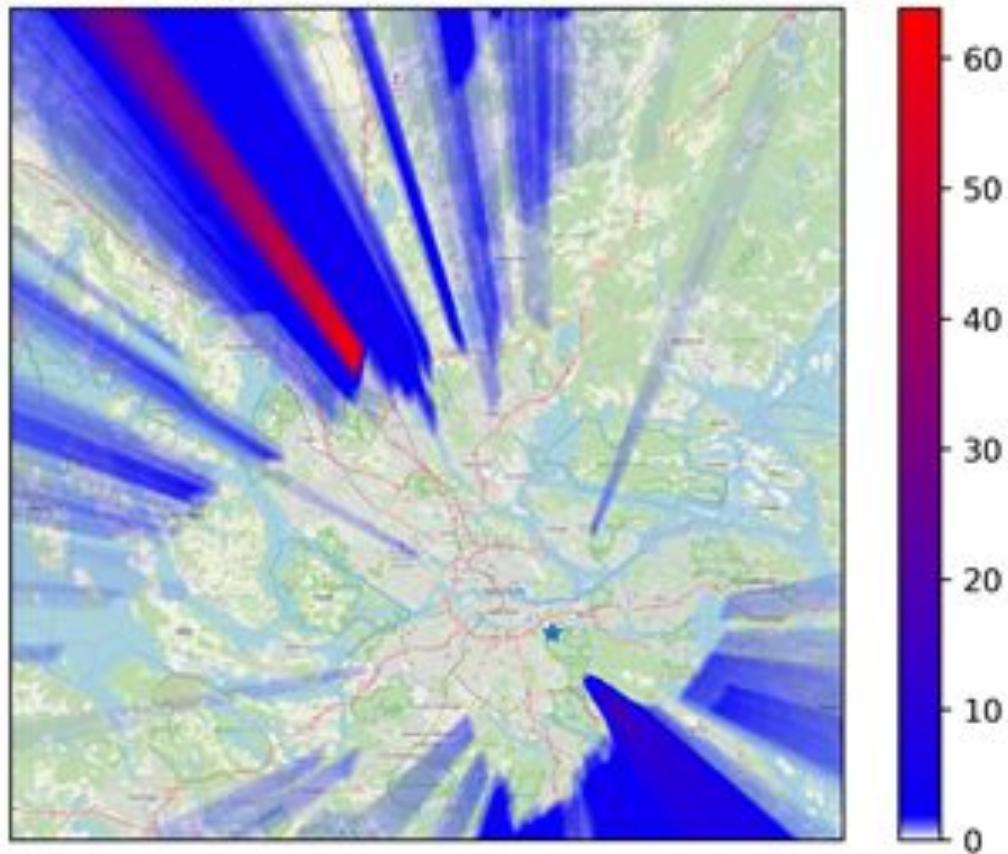
founding members



EFR

0/1, b&w

Expected Fatality Rate (altitude band 1000m-1100m)



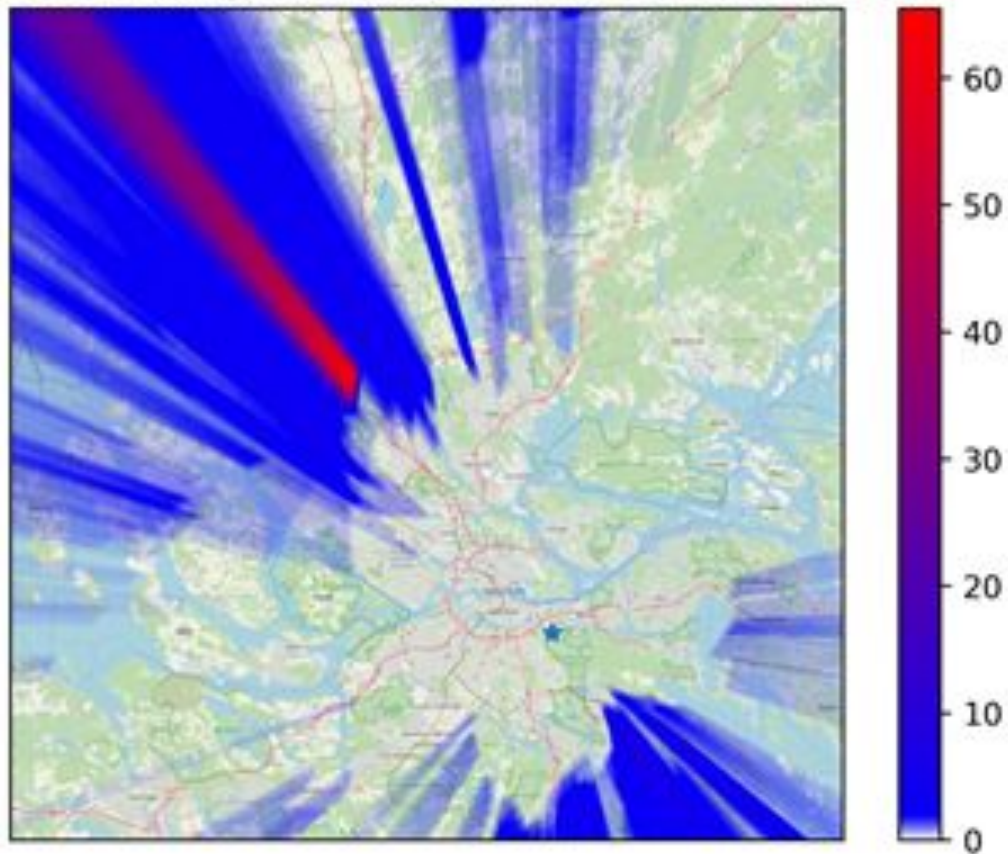
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 1100m-1200m)

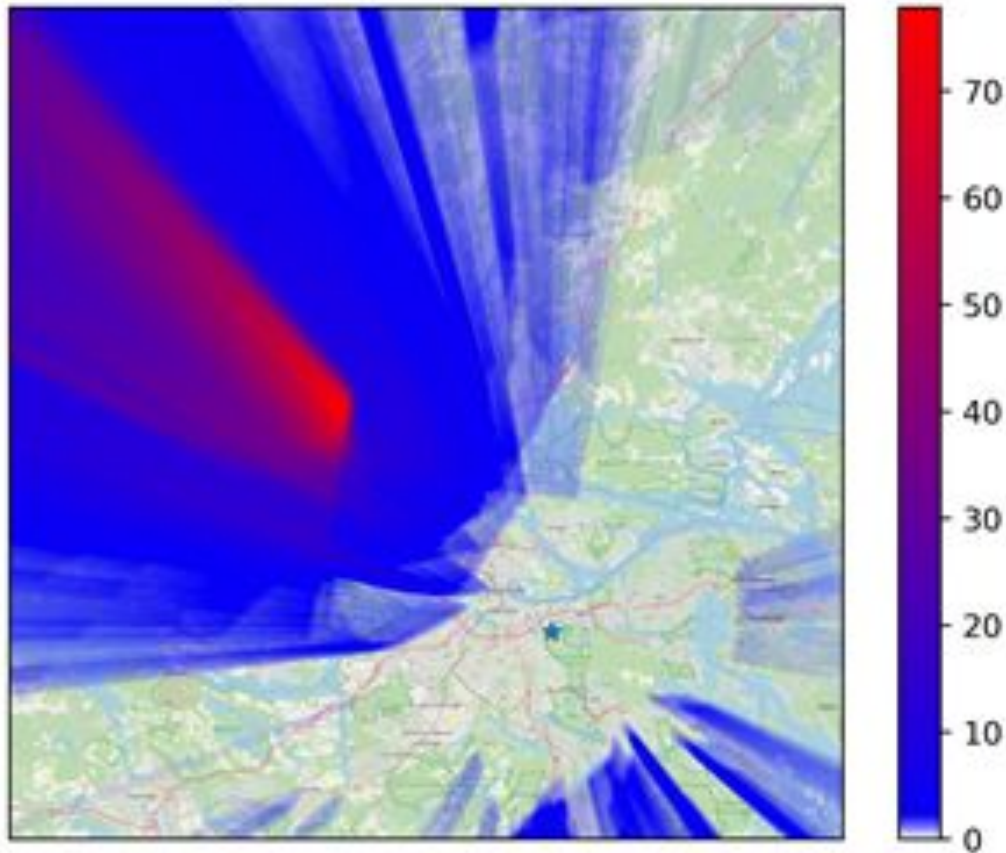


11th SESAR Innovation Days

EFR

0/1, b&w

Expected Fatality Rate (altitude band 1200m-1300m)



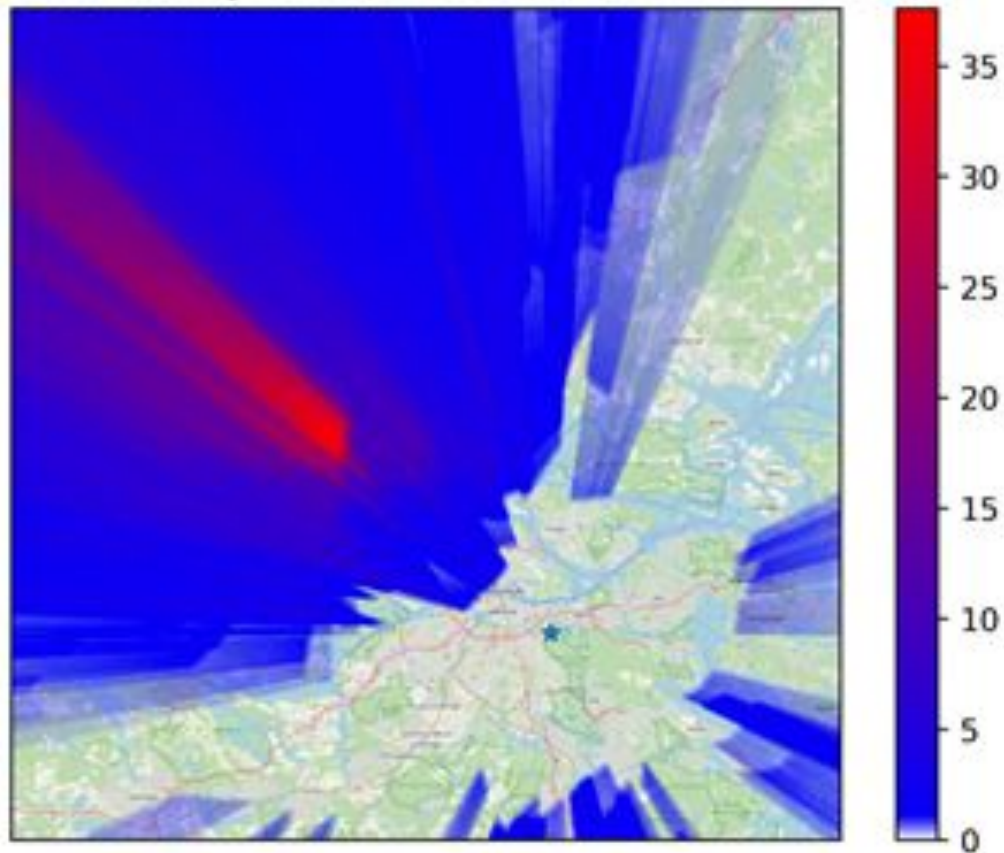
11th SESAR Innovation Days



EFR

0/1, b&w

Expected Fatality Rate (altitude band 1300m-1400m)



11th SESAR Innovation Days



EFR

0/1, b&w, simplistic air risk picture

quant POV: rather airspace availability

diff corridors (hot topic) on diff altitudes

discovered by alg, ~~hard-coded/decided~~

flip $\leftrightarrow$ through our maps

SORA

complex air risk procedure

overly? pilots are aware of risks

Fun fact: SORA1 -- simple(r); towards
2.0 avia professionals had a lot to say ;-)

Ground risk: new $\Rightarrow$? simple (overly?) in SORA

"def"? : pop area = "includes areas substantially used for residential, commercial or recreational purposes"

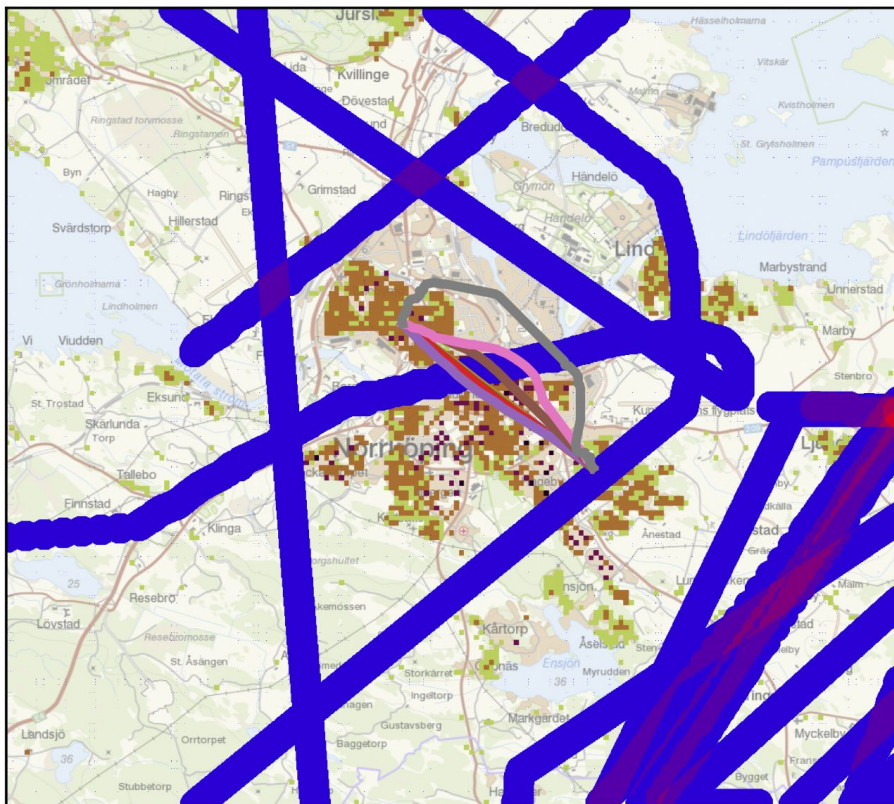
Finer-grained pop density? Go2 quant ground risk (where air risk is negligible)

EFR

0/4, b&w, simple air risk picture
Norrköping municipality (~10⁶ppl)

Ground risk
sole EFR contributor

Occupancy over 1 month



11th SESAR Innovation Days

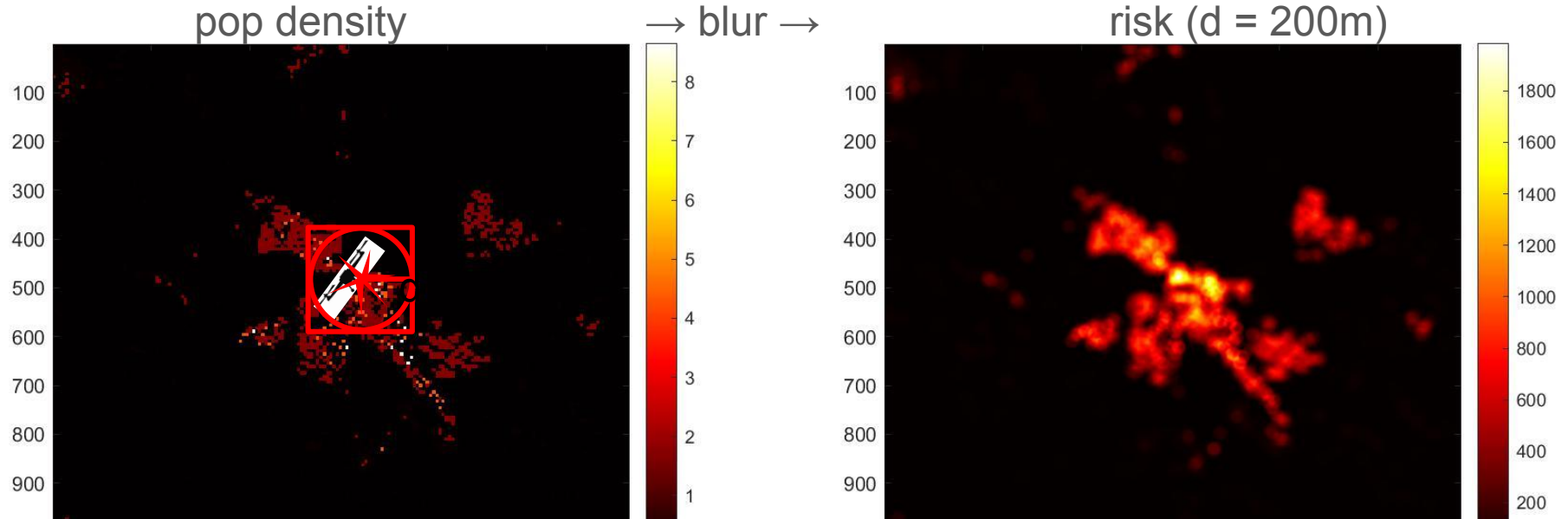
EFR remains the KPI

- [SORA1.0](#): The number of fatal injuries to third parties on ground (per flight hour) is chosen as the best parameter that can embody the equivalence of risk, when kept equal among the different categories
- [SORA2.0](#): The usual means to measure fatalities are by the # of deaths within a particular time interval (e.g. fatal accident rate per million flying hours), or ...
- [Arctic Science RPAS Operator's Handbook](#)
- [Weibel, Hansman. ATIO 2004]
- [Dalamagkidis, Valavanis, Piegl. Progress in Aerospace Sciences, 2008]
- ...

10^{-5} fatalities/hour

Risk map: $\forall q, E[\text{exposed} \mid \text{fails at } q] = \text{ppl within } d \text{ of } q$

possibly weighted by $P\{\text{fatality} \mid \text{struck}\}$ (if shelter et al. info available)



11th SESAR Innovation Days

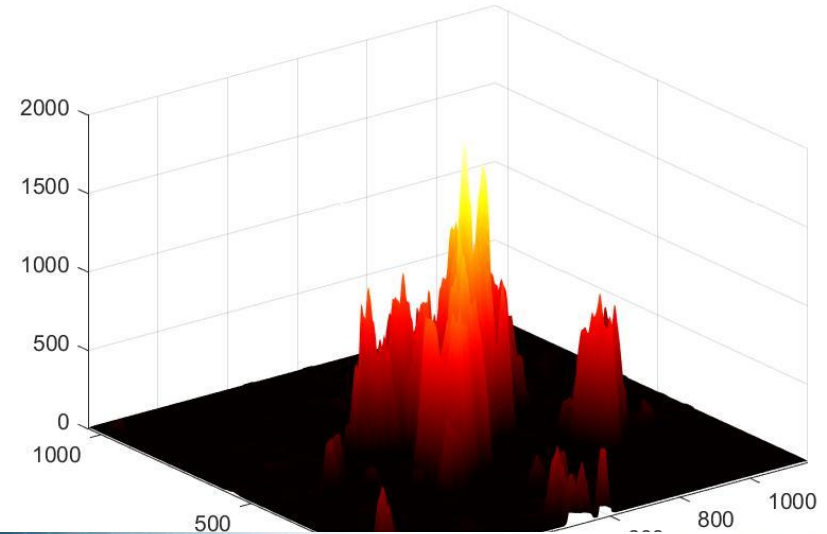
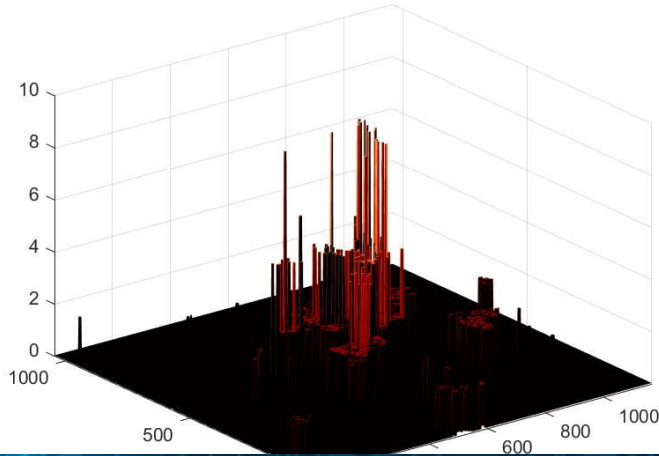
Risk surface: $\forall q, E[\text{exposed} | \text{fails at } q] = \text{ppl within } d \text{ of } q$

possibly weighted by $P\{\text{fatality} | \text{struck}\}$ (if shelter et al. info available)

pop density

→ blur →

risk (d = 200m)

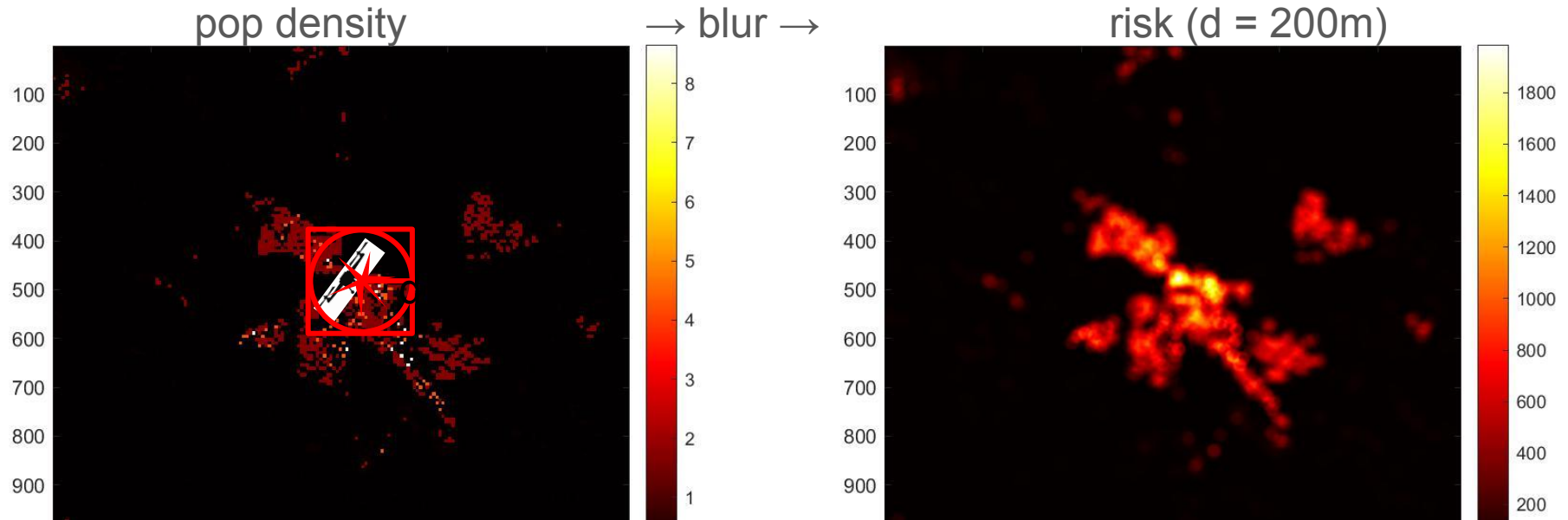


11th SESAR Innovation Days



Risk map: $\forall q, E[\text{exposed} \mid \text{fails at } q] = \text{ppl within } d \text{ of } q$

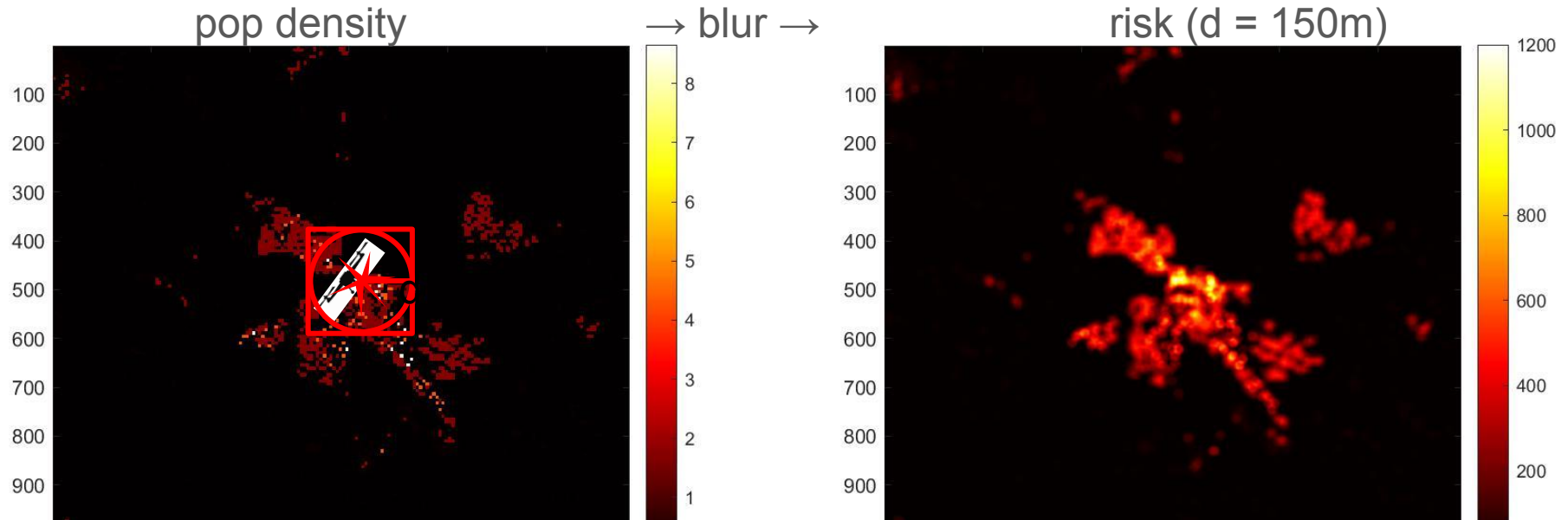
possibly weighted by $P\{\text{fatality} \mid \text{struck}\}$ (if shelter et al. info available)



11th SESAR Innovation Days

Risk map: $\forall q, E[\text{exposed} \mid \text{fails at } q] = \text{ppl within } d \text{ of } q$

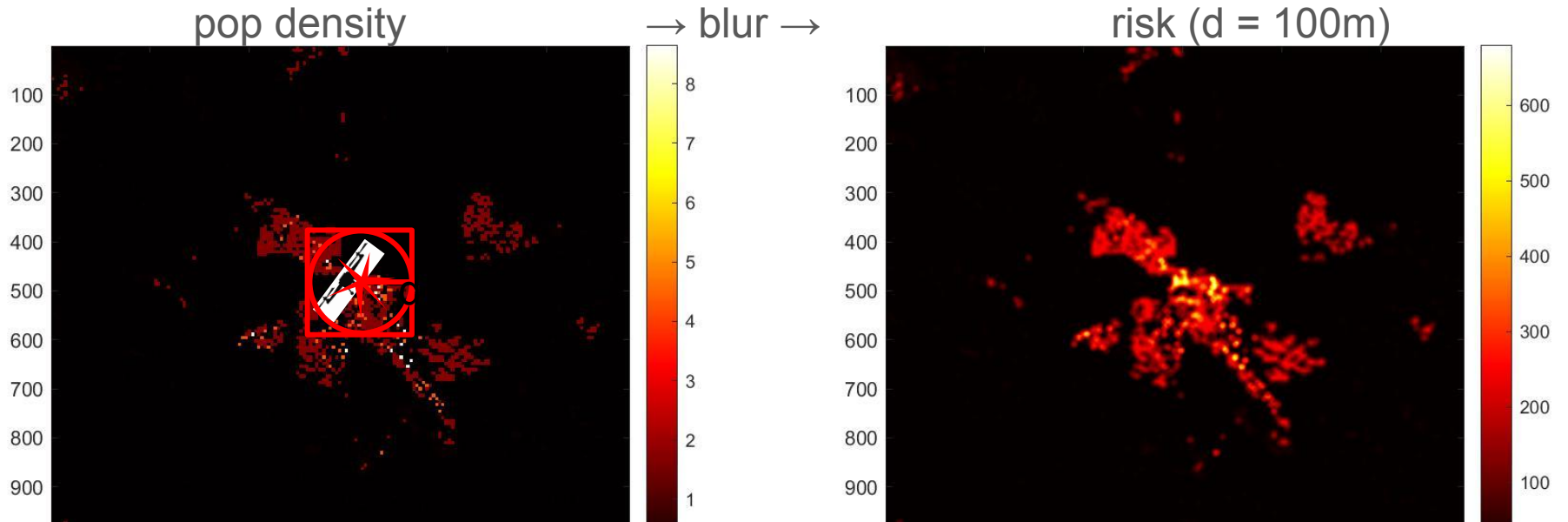
possibly weighted by $P\{\text{fatality} \mid \text{struck}\}$ (if shelter et al. info available)



11th SESAR Innovation Days

Risk map: $\forall q, E[\text{exposed} \mid \text{fails at } q] = \text{ppl within } d \text{ of } q$

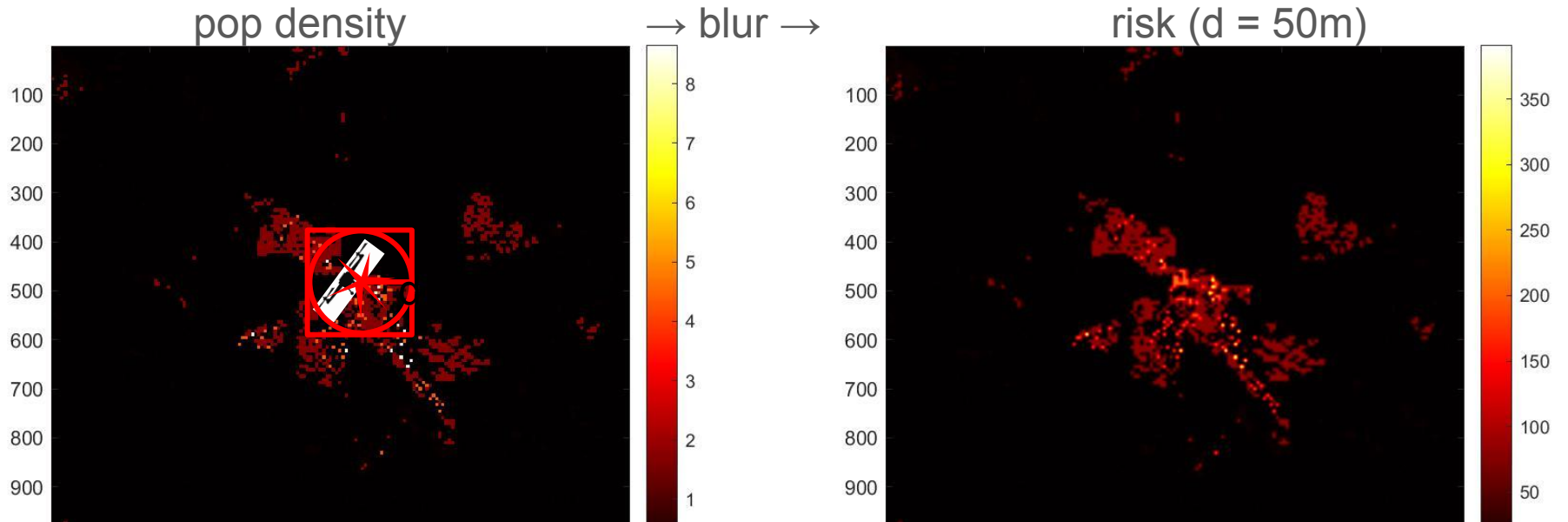
possibly weighted by $P\{\text{fatality} \mid \text{struck}\}$ (if shelter et al. info available)



11th SESAR Innovation Days

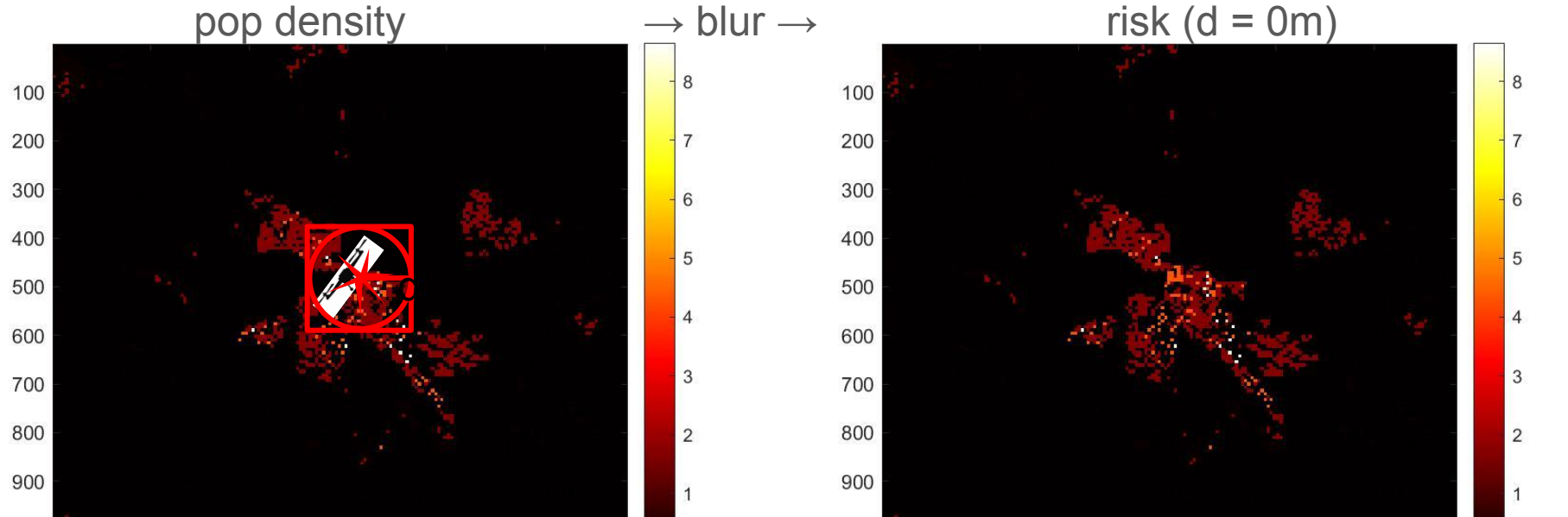
Risk map: $\forall q, E[\text{exposed} \mid \text{fails at } q] = \text{ppl within } d \text{ of } q$

possibly weighted by $P\{\text{fatality} \mid \text{struck}\}$ (if shelter et al. info available)



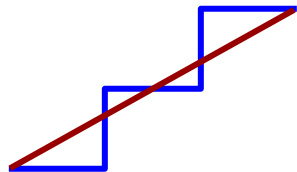
Risk map: $\forall q, E[\text{exposed} \mid \text{fails at } q] = \text{ppl within } d \text{ of } q$

possibly weighted by $P\{\text{fatality} \mid \text{struck}\}$ (if shelter et al. info available)

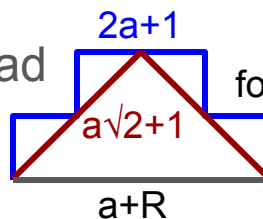
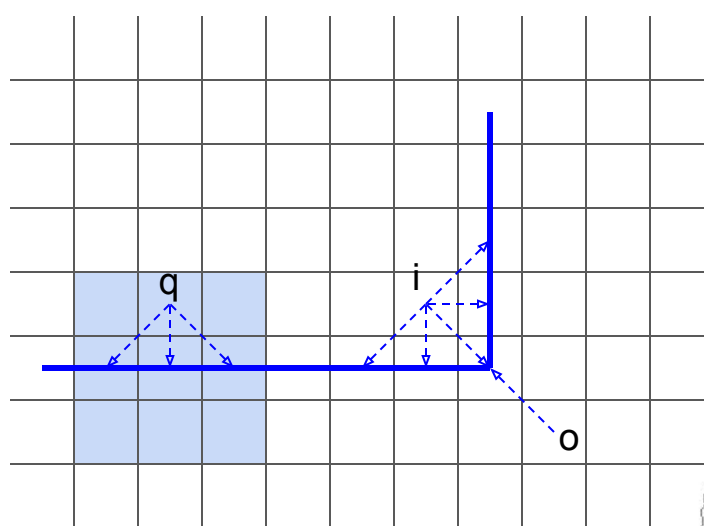


11th SESAR Innovation Days

Grid paths

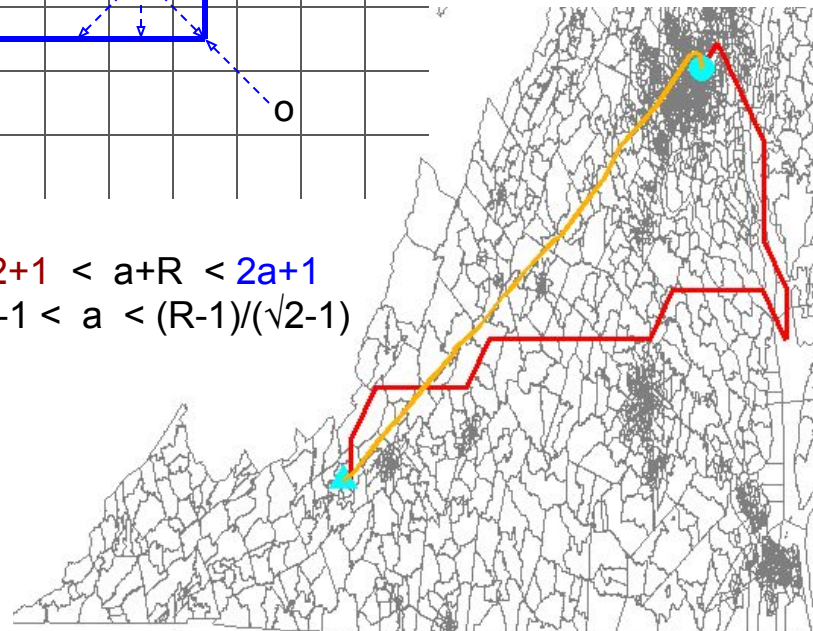


- **L** error up to ~40%
- many turns -- unnatural
(`raster2vec straightfwd`)
- incorrect risk when converted
(over/undercount in/out)
- min $a \cdot L + \text{risk}$ path may mislead
(have high risk $R \gg 1$)
- + Easy to compute



$$a\sqrt{2}+1 < a+R < 2a+1$$

for $R-1 < a < (R-1)/(\sqrt{2}-1)$



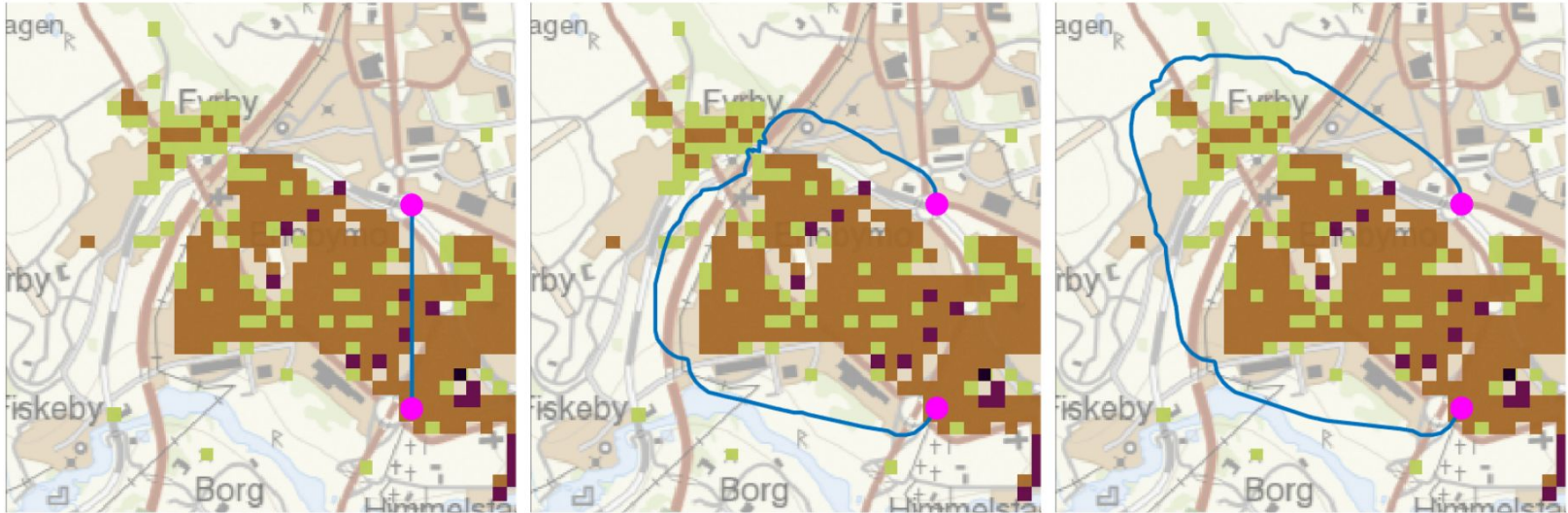
More connections: issues ↘ but remain

[[Rudnick-Cohen, Herrmann, Azarm'16](#)]

[LiU+NASA ATMS'21] ([Slides](#))

Grid-routing

Representative paths (discovered by alg, ~~hardcoded/decided~~)



11th SESAR Innovation Days



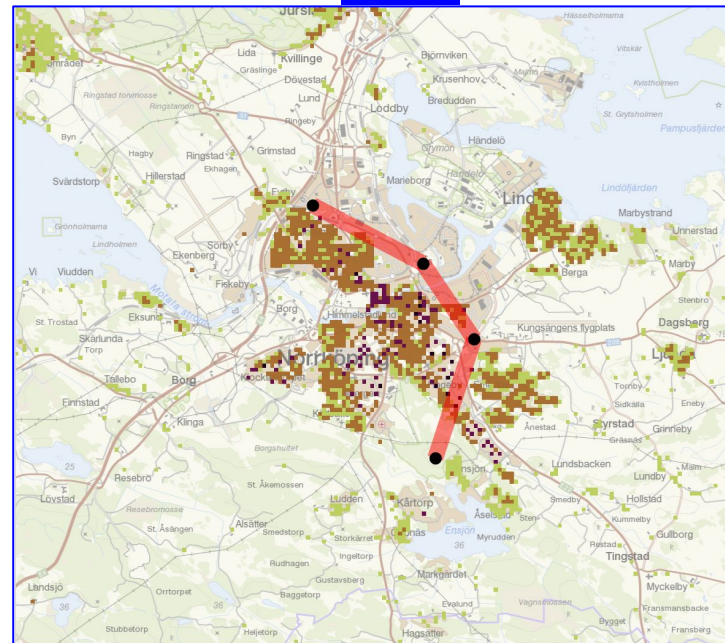
[LiU+NASA ATMS'21] ([Slides](#))

Options ∇ mission

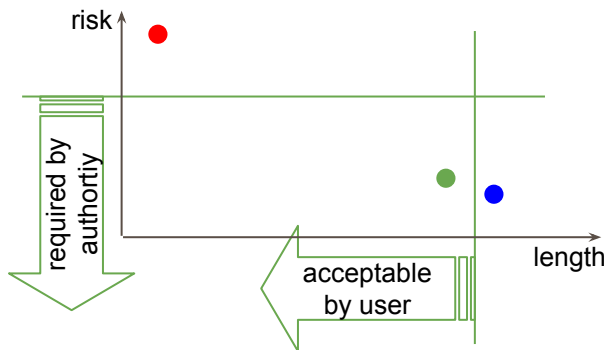
EFR vs Length tradeoff, Pareto-opt paths

- min EFR for given L
- min L for given EFR

GUI



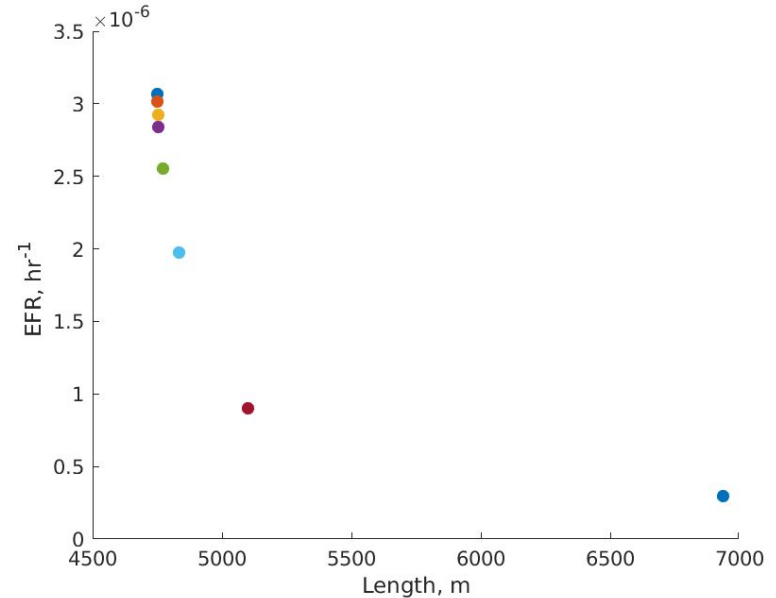
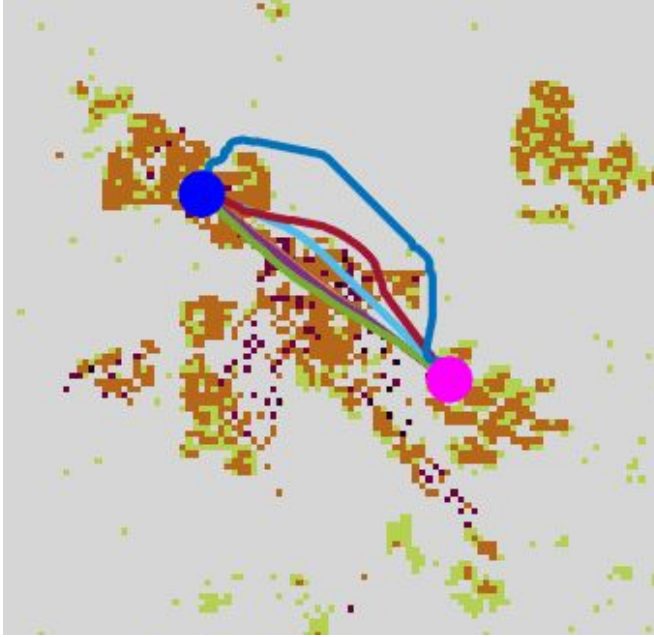
Exposed population: 4341
Affected area: $3.395 \times 10^6 \text{ m}^2$
Exposed population density: $1.279 \times 10^{-3} \text{ ppl/m}^2$
Linear density: $5.116 \times 10^{-1} \text{ ppl/m}$



11th SESAR Innovation Days

Qual methods discouragement: why reducing EFR?

Endpts in densely pop area $\Rightarrow$ GRC=6 $\Rightarrow$ all routes equal from qual POV :-)



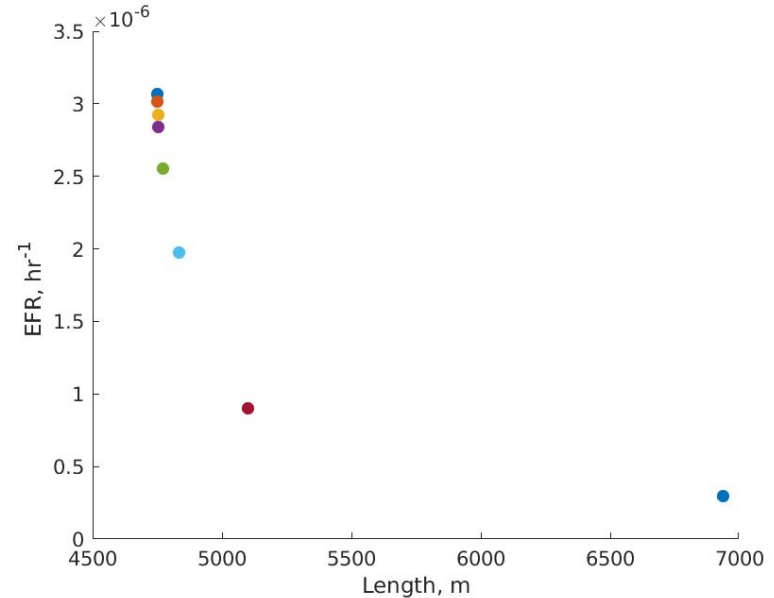
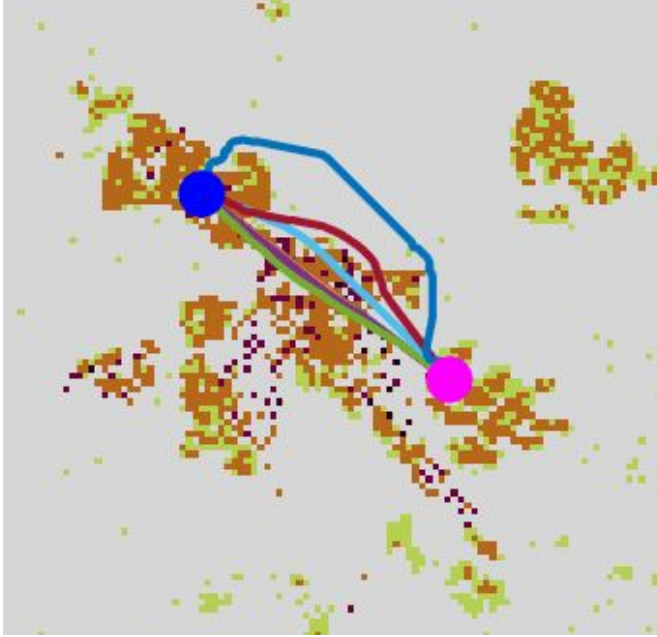
cf. SORA's discouragement?

[[CORUS](#) Section 2.2.2.c]: "drone operations in ARC-c or ARC-d offer little motivation for an operator to reduce the GRC, as the SAIL stays almost unaffected"

SAIL determination				
	Residual ARC			
Final GRC	a	b	c	d
≤2	I	II	IV	VI
3	II	II	IV	VI
4	III	III	IV	VI
5	IV	IV	IV	VI
6	V	V	V	VI
7	VI	VI	VI	VI
>7	Category C operation			

Fix: mandate quant RA (+ to SORA)

Use longer but safer route (among SORA-approved)



Fix: mandate quant RA

Encourages using computerized tools
(in practice: mandates,
sans mental calculation enthusiasts)
for mission

- planning (operator)
- approval (regulator)

In line with emphasis on

- automation
- digitalization

in UTM

▷ very def of U-space service as one
"relying on digital services and
automation of functions designed to
support safe, secure and efficient
access to U-space airspace for a
large number of UAS" [664]

~~Fix: mandate quant RA~~

- automation
- digitalization

risk being empty hype words in defs,
while

- RA
- operation approval

done with pen and paper
(Thank you SORA for early-stage
opportunity to use qual methods, but)

Future: computerized services

- optimize the performance
- minimize the adverse impacts

of drone proliferation

CORUS: list U-space services

E.g., “GRC can be reduced easily
using the information provided by
certain U-space services.”

Pareto opt tool above:

contribute to such services,
specifically targeted at ground risk

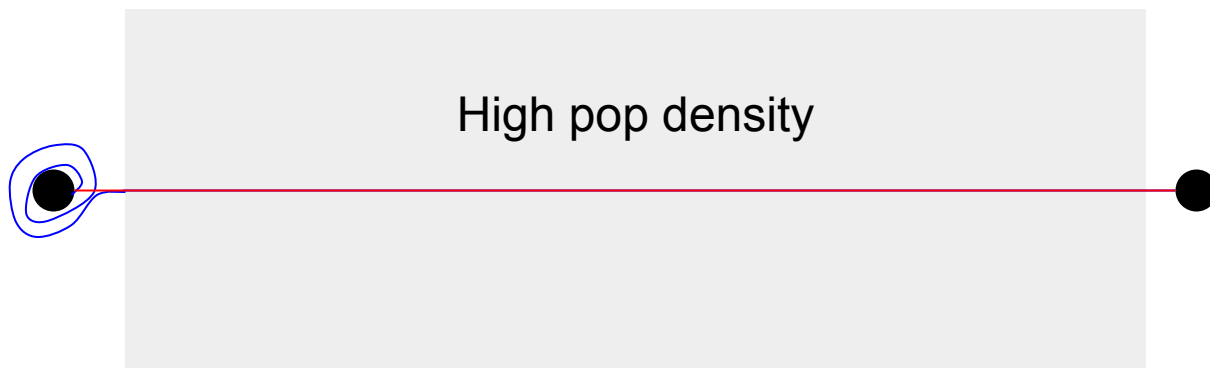


Quant flow

High EFR

Low EFR

per flight hour



Quant flaw and a fix: mandate Pareto opt

Logic: forbid "unduly long" = ~~Pareto opt~~

Acceptance $\Leftarrow$ ~~excessive flying~~

- Regulator: Pareto opt tool above
- Operator: pen&paper planning?

Fair to favor better-equipped (PBS)

(may apply to delivery only, but...

~~excuse~~



High pop density

Not approved

break the paradigm

"regulations don't

care about your

business" :-(...)

Discussion needed...

Discussion/Conclusion: qual $\leftrightarrow$ quant RA

Qual, easier (for stakeholders) to

- consider
- think about
- envision
- describe
- mandate?
we suggest
+ quant

Closer
than one
might think

Quant, easier (for researchers) to

- digitize
- automate
- computerize
- formalize
- model mathematically with rigor
- numerically calculate
- have algorithms for
- use data-driven approaches for