Noise simulation for UAM integration

Application to a health-care logistics system

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KTH VETENSKAP OCH KONST

Agenda

- Background:
  - ✓ Drone noise characterization
  - ✓ Health-care use-case
- Fixed wing drone as a noise source
- Calculation methodology and results
- Benchmark to reference values
- Conclusion and outlook

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Different drone concepts

Legend	OEM	Vehicle
1	Airbus	CityAirbus
2	Airflow	Model 200
3	Archer	Maker
4	Bell	4EX
5	Beta Technologies	Alia S250c
6	Dufour Aerospace	aEro 3
7	Ehang	EH-216
8	Ehang	VT-30
9	Electra	eSTOL
10	Elroy Air	Chaparral
11	Eve Urban Air Mobility Solutions	Eve
12	Hyundai Urban Air Mobility	S-A1
13	Jaunt Air Mobility	Journey
14	Joby Aviation	S4
15	Lilium	Jet
16	Overair	Butterfly
17	Pipistrel	Nuuva V300
18	Sabrewing Aircraft Company	Rhaegal RG-1
19	Vertical Aerospace	VA-X4
20	Volocopter	VoloCity
21	Volocopter	VoloConnect
22	Wisk	Cora

Acoustic source models need to be adapted to the propulsion concept!

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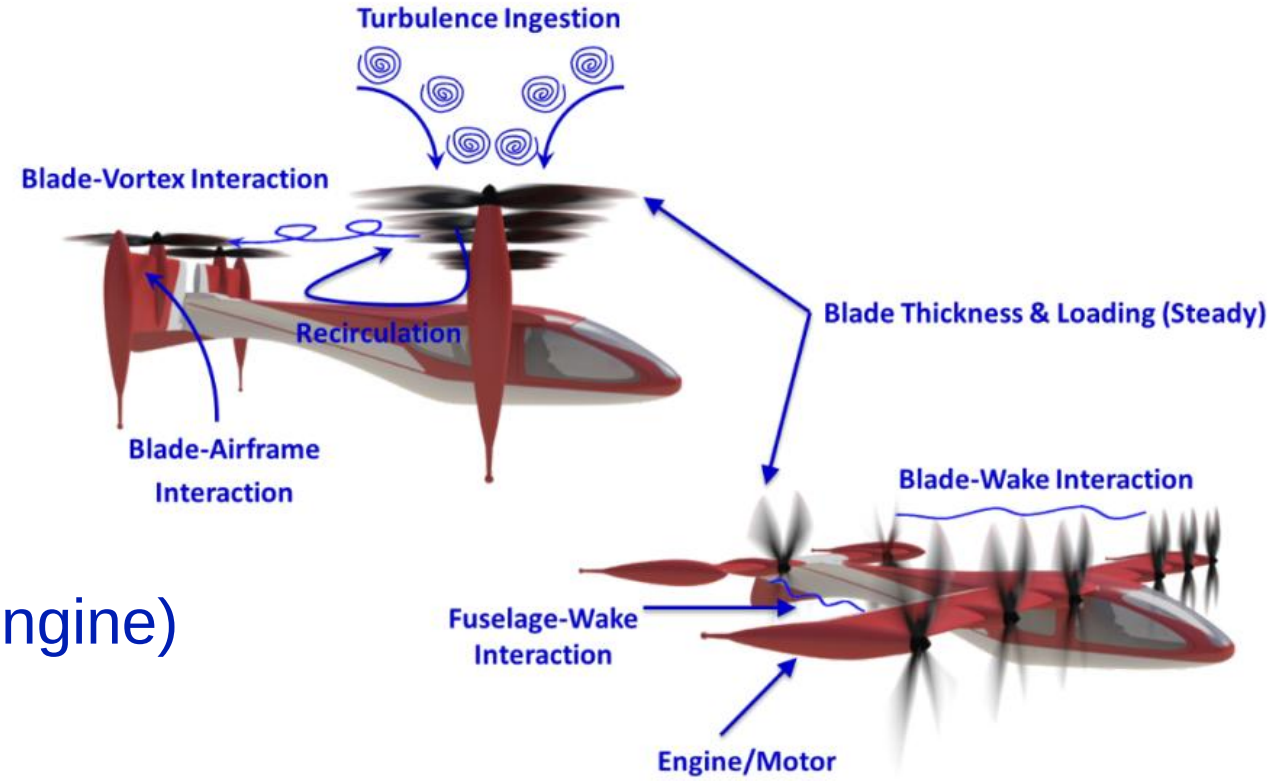
Drönarbuller: vad är det som låter

- Self generated rotor/propeller noise
- Interaction between airflow and fuselage
- Interaction between blades and turbulence



NB: Typically the drive system (motors/engine) is not contributing significantly.

https://ntrs.nasa.gov/api/citations/20205007433/downloads/NASA-TP-2020-5007433.pdf

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Cargo drones

Single-mode cargo drones (multicopters):

- Fixed lifting rotors (loud)

Dual mode cargo drones:

- Lifting rotors (loud)
- Pulling/pushing propellers (relatively silent)

https://www.hongfeidrone.com/agricultural-drone/page/6/

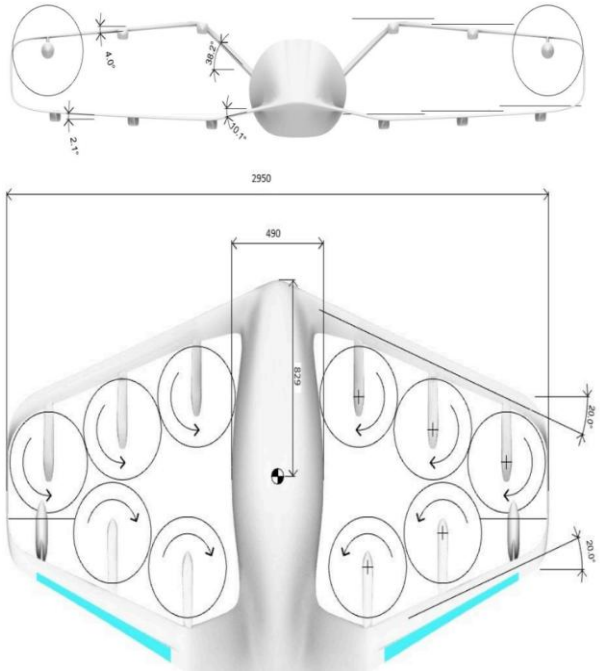
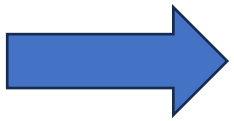


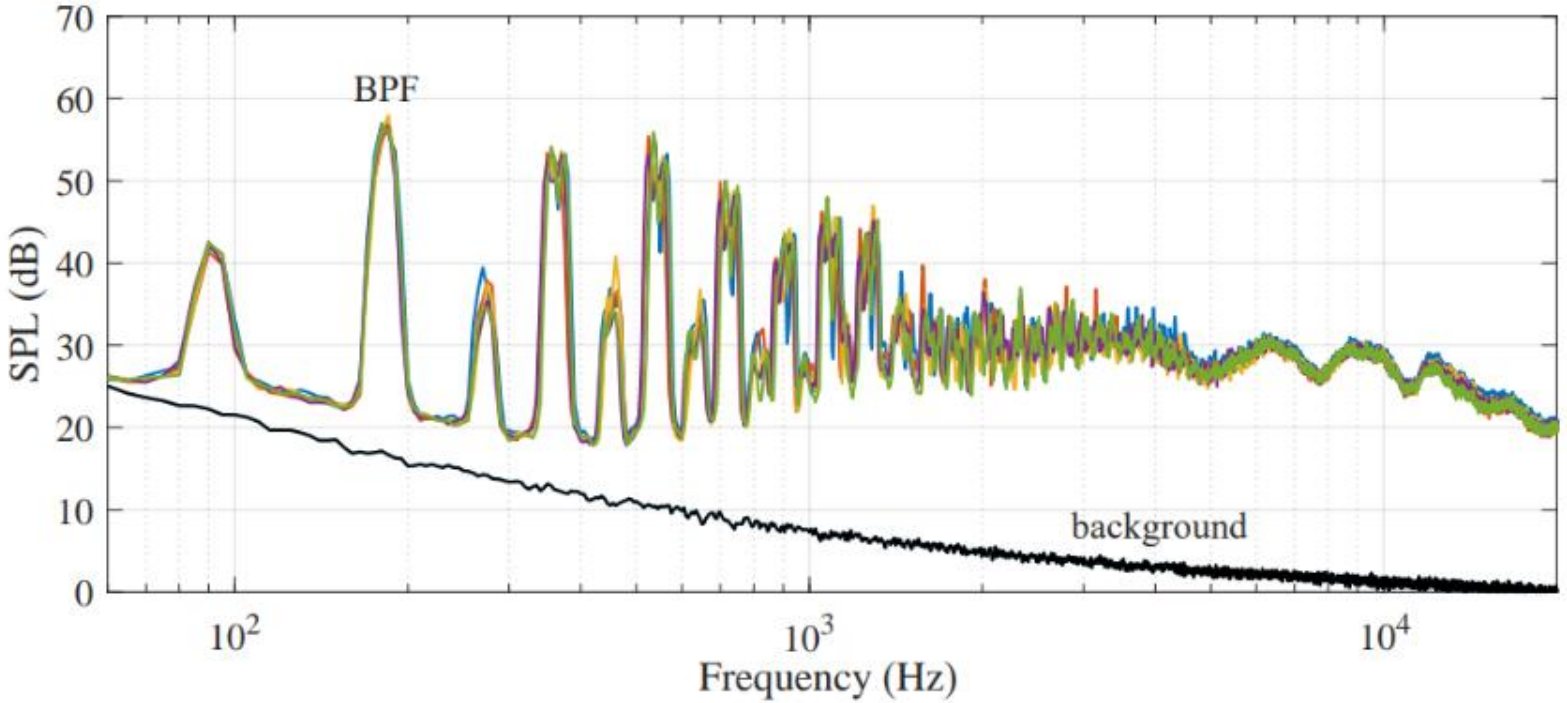
Foto Gustav Wiberg

UAV source spectrum

- Highly tonal spectrum



- Increased annoyance in relation to e.g. jet aircraft



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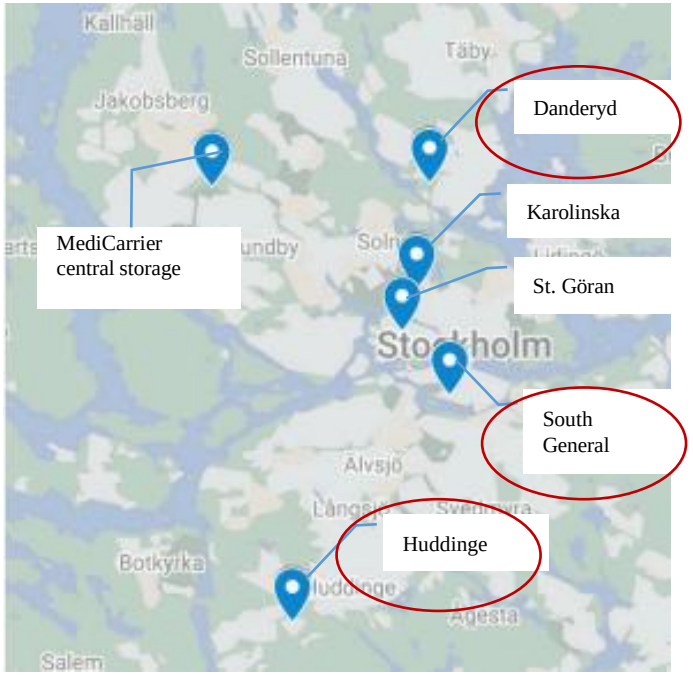
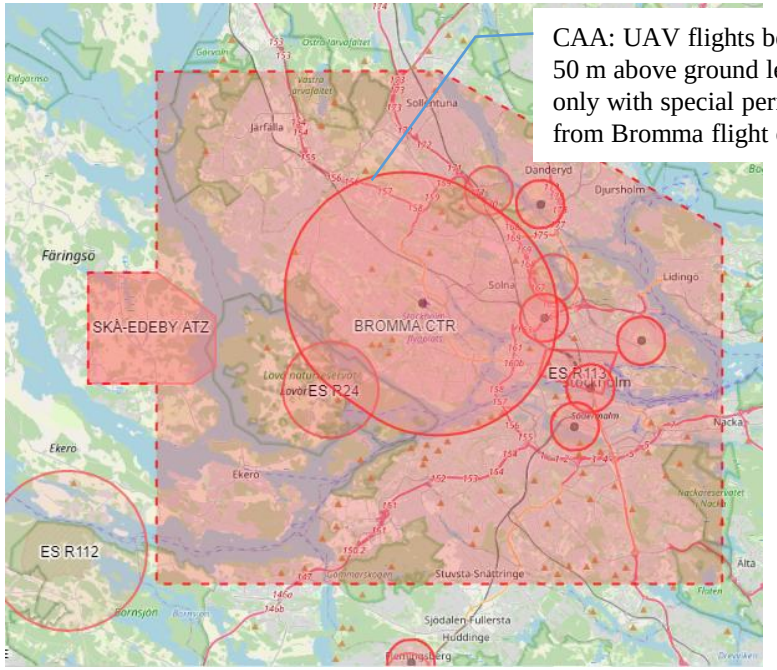
Stockholm health-care UAV use-case

- Five main acute Stockholm hospitals+ logistics center
- More than 5 000 packages delivered yearly, of which 98% weighs less than 2 kg
- Crucial items: blood samples or material and equipment from suppliers or other hospitals.
- Use-case: Replacing most of ground transport with UAV logistics[1)]
- Here: Focus on three non-central hospitals due to CAA restrictions.





[1)] Pre-study regarding drone transport between Stocholm acute hospitals

Health-care delivery use-case scenario:

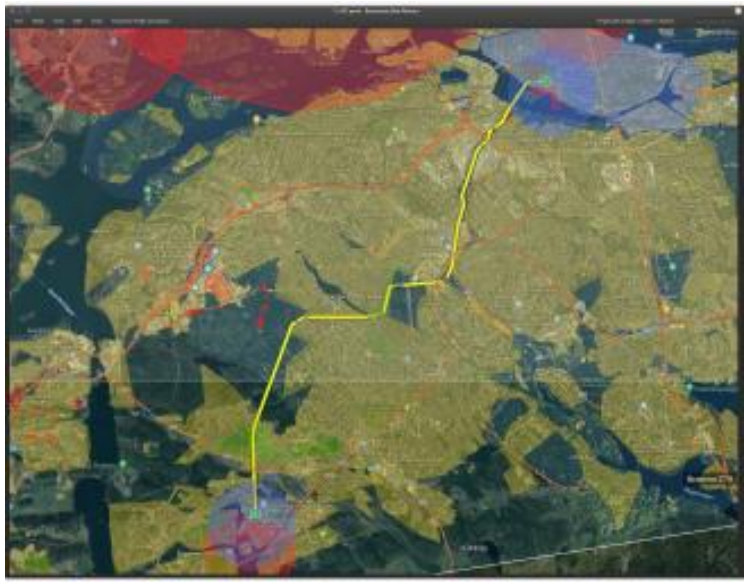
Yearly number of deliveries (m < 2 kg)

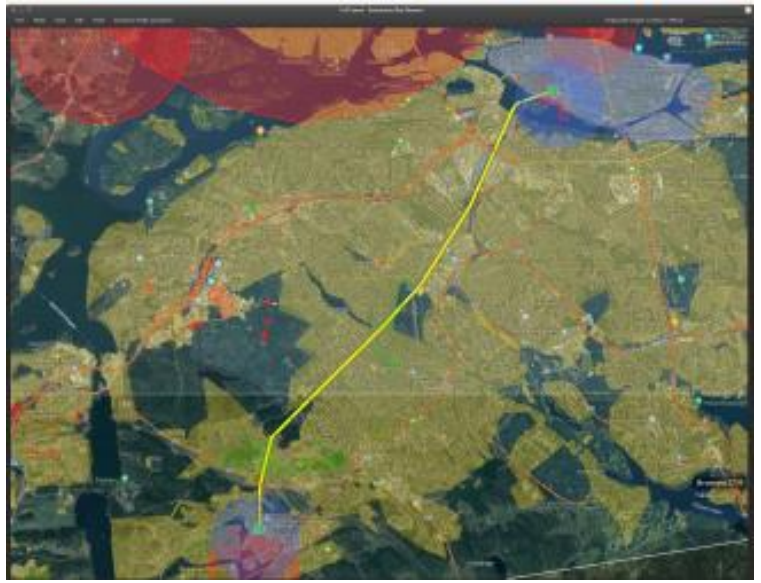
	Huddinge			South General			Danderyd			
	To	From	Total UAV	To	From	Total UAV	To	From	Total UAV	**Overall UAV**
Huddinge				401	715	1674	15	4	28	**1702**
South General	715	401	1674				271	625	1344	**3018**
Danderyd	4	15	28	625	271	1344				**1372**

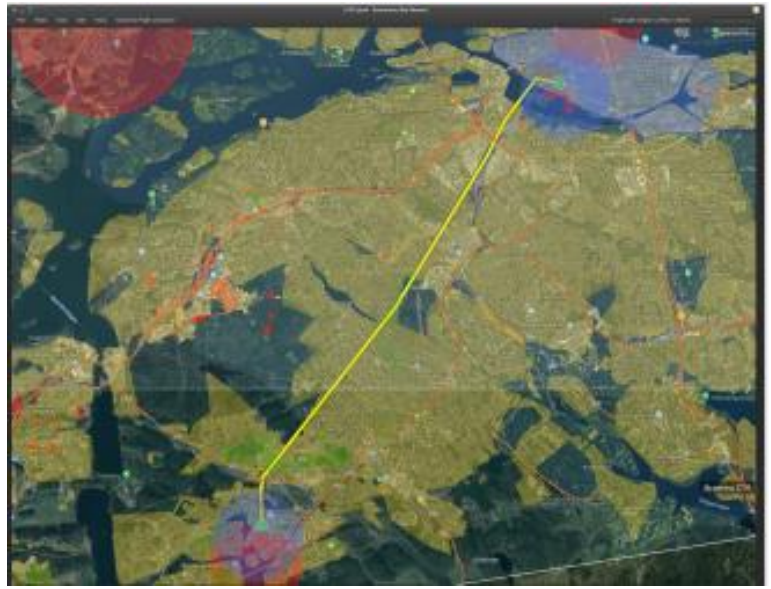
Assumptions:

- ❑ Due to weather limitations (risk of icing) 75% of the total number of deliveries can be made by UAV transport whereas the rest must be transported by standard ground delivery solutions.
- ❑ Ca 50% of UAV deliveries return empty (urgency requirement)

Health-care delivery use-case : Candidate routes: Huddinge - South General







Routes: Low ground risk (left), medium ground risk (center and right). Densely populated areas are marked with a blue colour.

Low ground risk: SAIL2 drones sufficient

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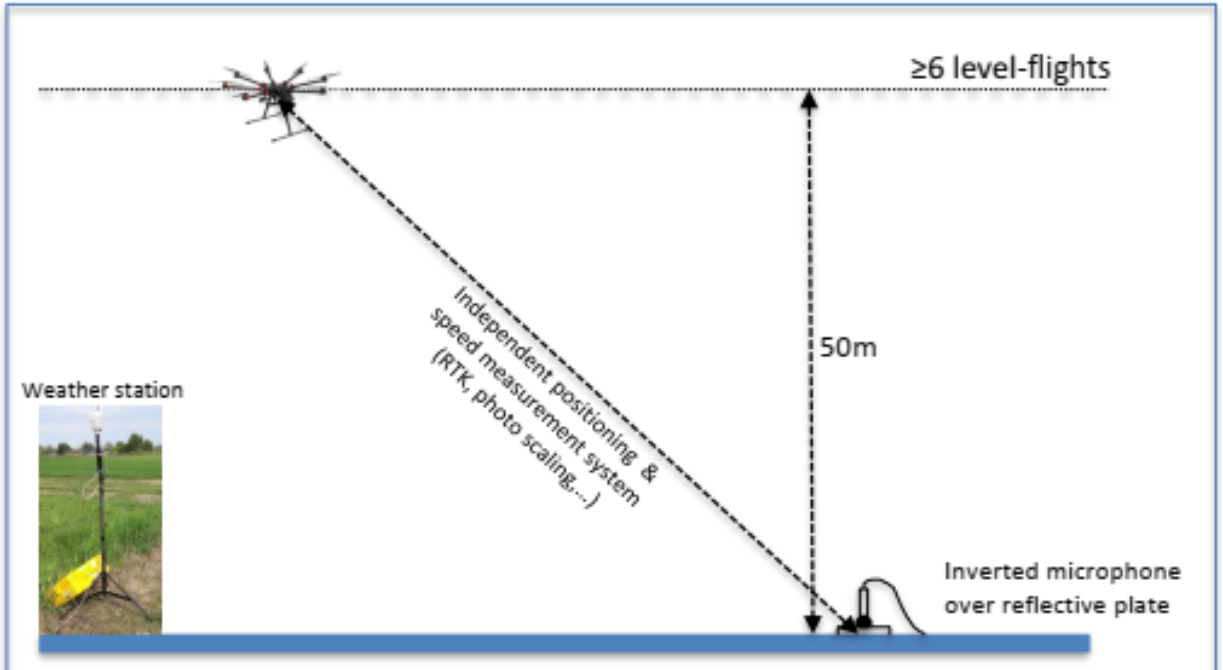
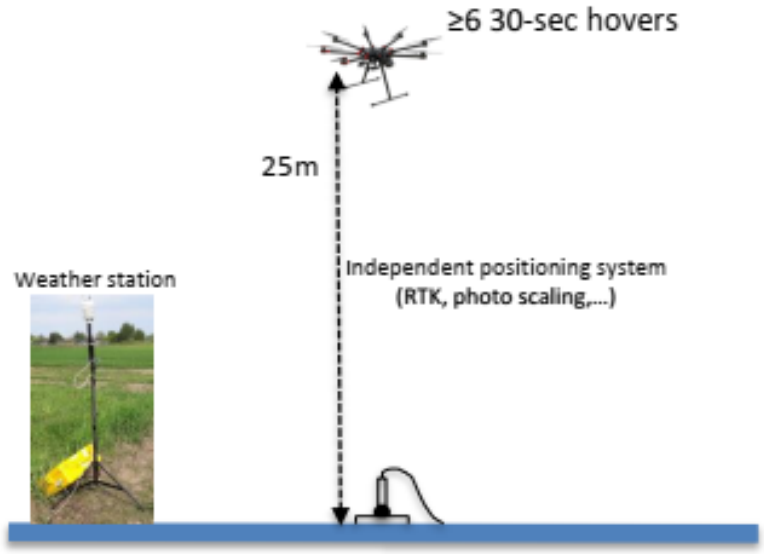
EASA: Measurement guidelines (from 2023)

Noise measurement procedures



Mandatory Level-Flight procedure with post-test noise adjustments for:
- Distance.
- Atmospheric absorption.
- Duration correction.
- Speed.

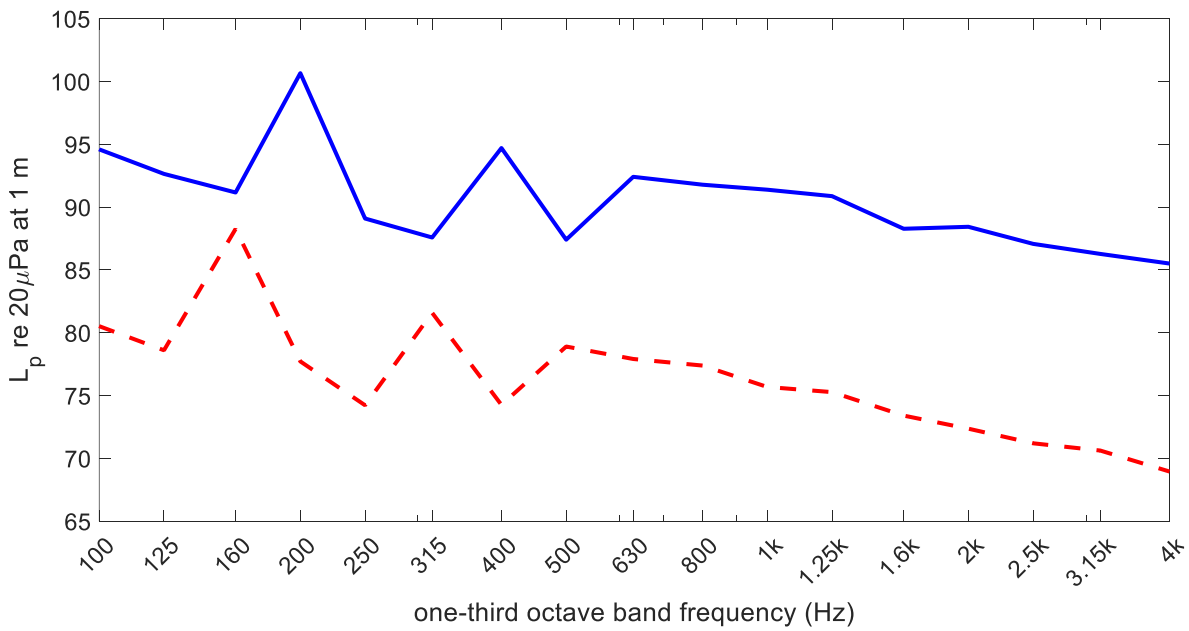


For UAS capable of stationary flight, Hover procedure with post-test noise adjustments for:
- Distance.
- Atmospheric absorption.

Field measurements according to EASA guidelines

Fixed wing delivery drone: 20 kg MTOL, 2 kg payload.

- No spectral data available from EASA test: Calculated sound pressure spectra based on tonal noise components (rotor RPM => fundamental blade passing frequency and harmonics)
- Levels tuned to field test dBA measurements (EASA guidelines)
- Added sound power at take- off estimated from test bench data with 10 % increase of thrust vs. hover



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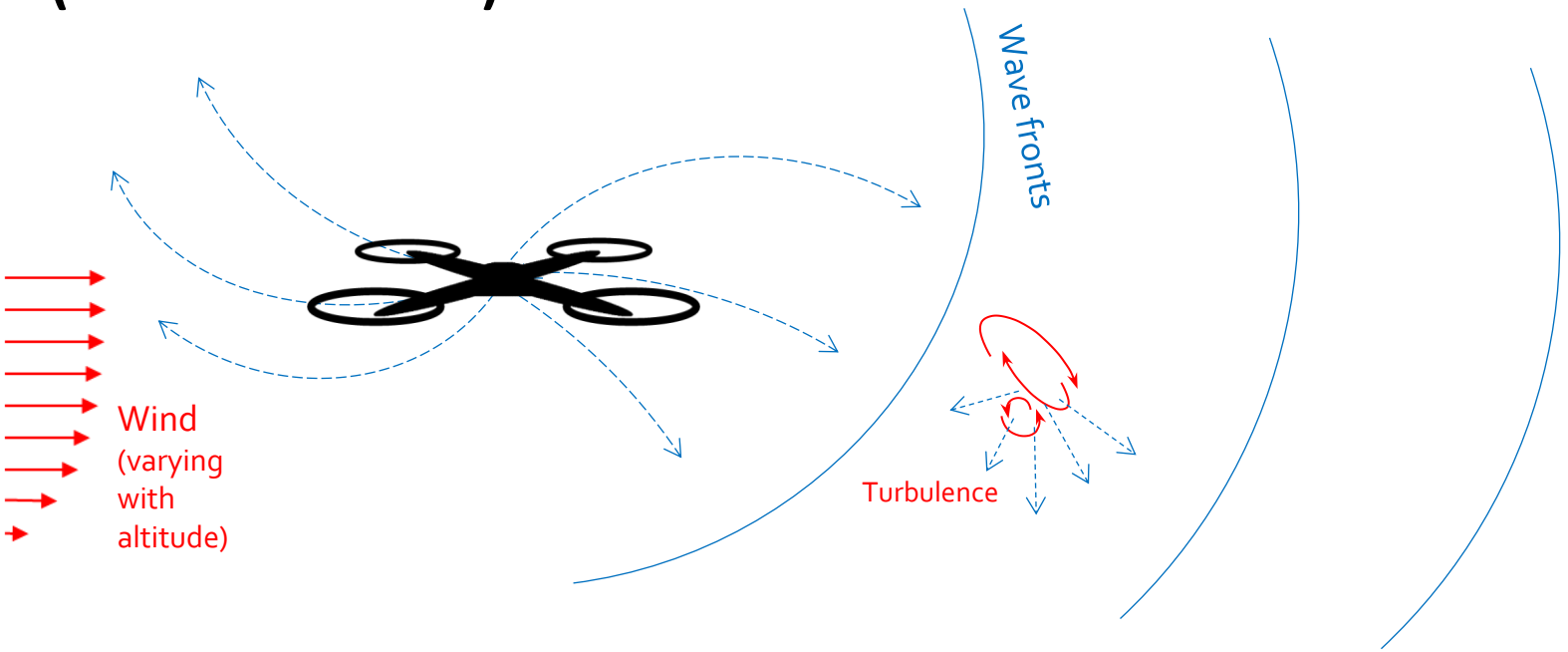
Air vehicle noise mapping. Principles for simulation method

Sound source → (sound emission) **sound propagation** **→** **sound immission (reaching ground/people,…)**



Sound source model and time discretised flight trajectory

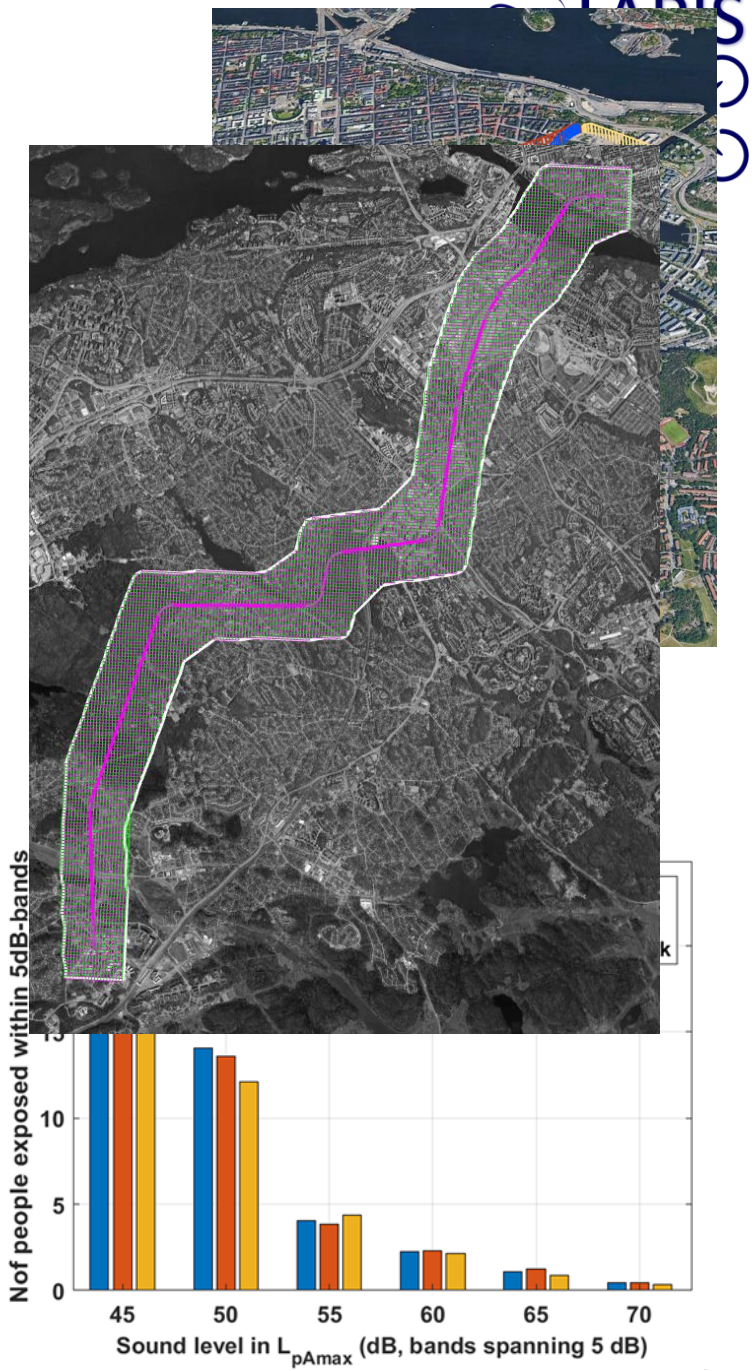
Sound propagation model, spherical or refractive spreading, absorption – ground and screening effects

Sound spectrum time histories in ground grid and
Noise contours in noise metric wanted

Further analysis …

Bullersimuleringar med SAFTu

- SAFTu - har utvecklats i APIS projektet (vidareutveckling av SAFT[1])
- Input: Källkaraktäristik, flygväg, populationsdata, topografi, (meterologiska data)
- Metodik: Strålgångsberäkning till adaptivt marknät, ”grid”
- Beräknade resultat:
  - Ljudhistorik i samtliga grid-punkter
  - Konturlinjer (ljudnivåkurvor) av önskat ljudnivåmått ($L_{amax,}$ L_{DEN} etc)
  - ΔdB_{21} mellan olika fall, t.ex. två olika UAV:er, två olika flygprofiler.
  - Antalet boende inom olika ljudnivåintervall

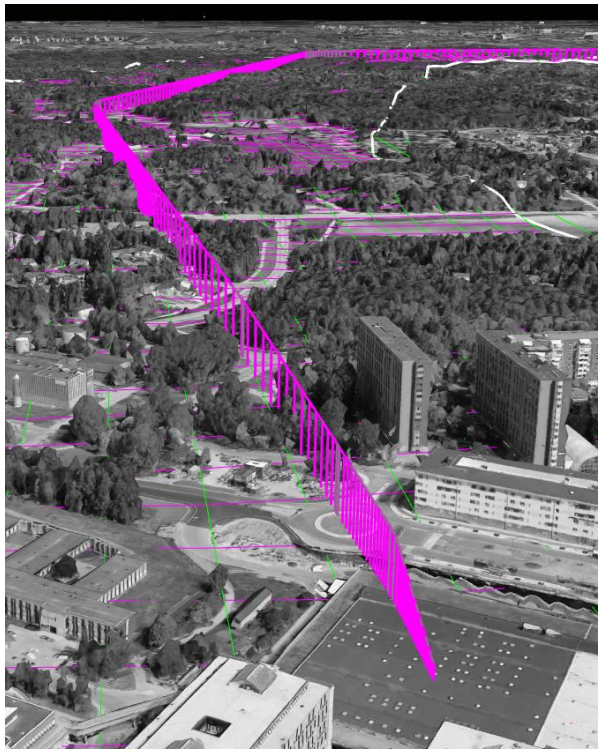


[1] SAFT : **S**imulering av **A**tmosfär och **F**lygtrafik för en **T**ystare omgivning
se länk: Aircraft noise mapping code SAFT

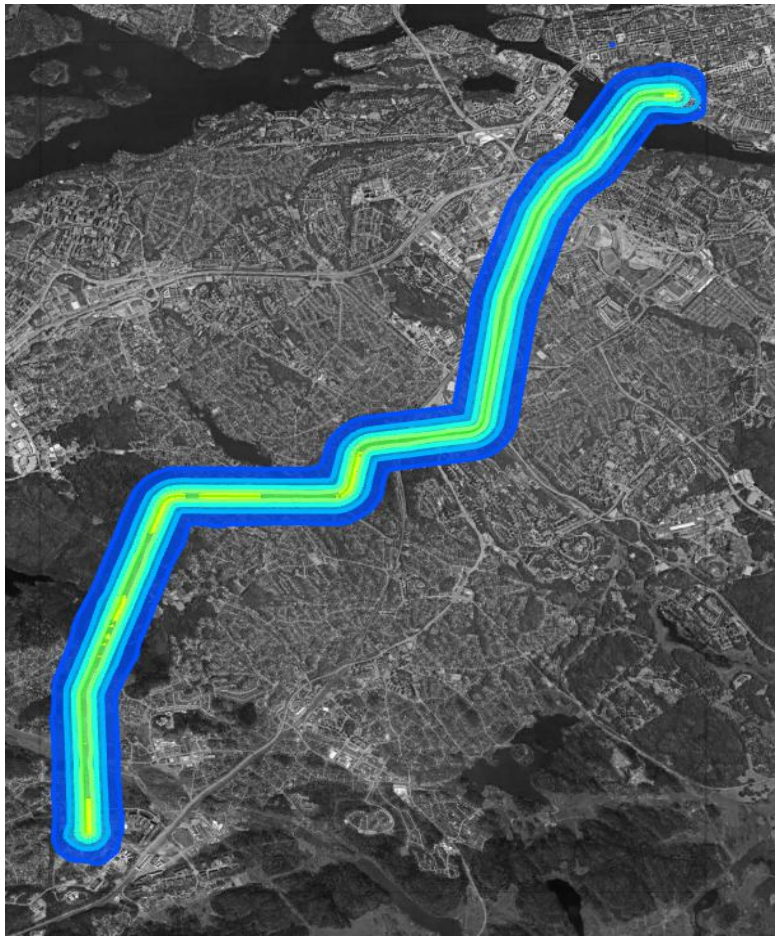
Huddinge- South General: (low ground risk route)

- Flight height above ground 40-60 m
- Two different operational modes: Major sound reduction using wing mode

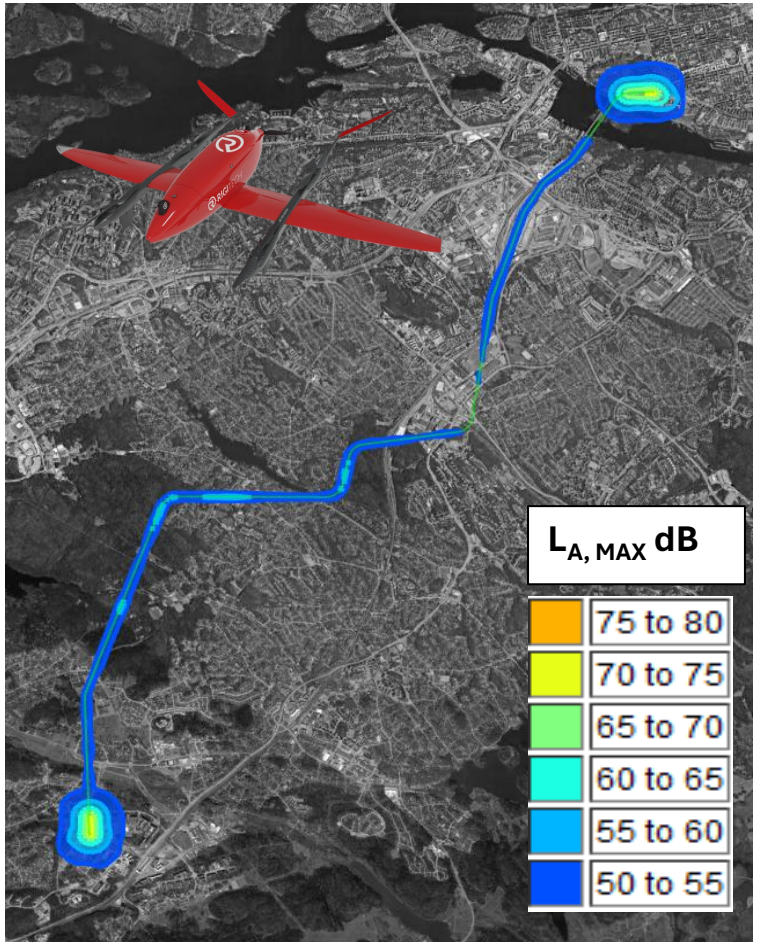
Trajectory at starting point



Quadcopter mode the entire way



Transition to wing mode.



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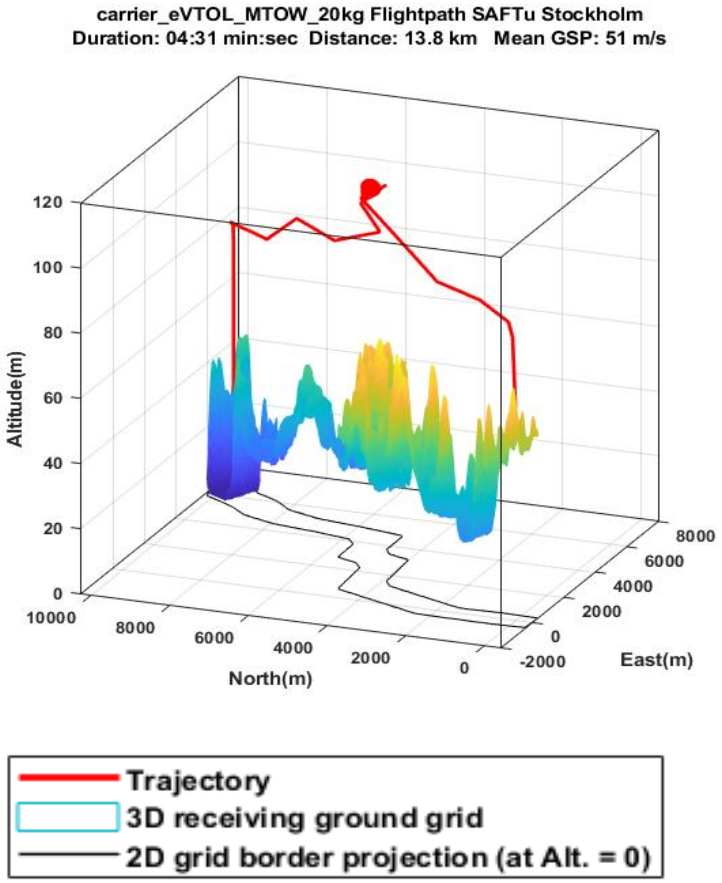
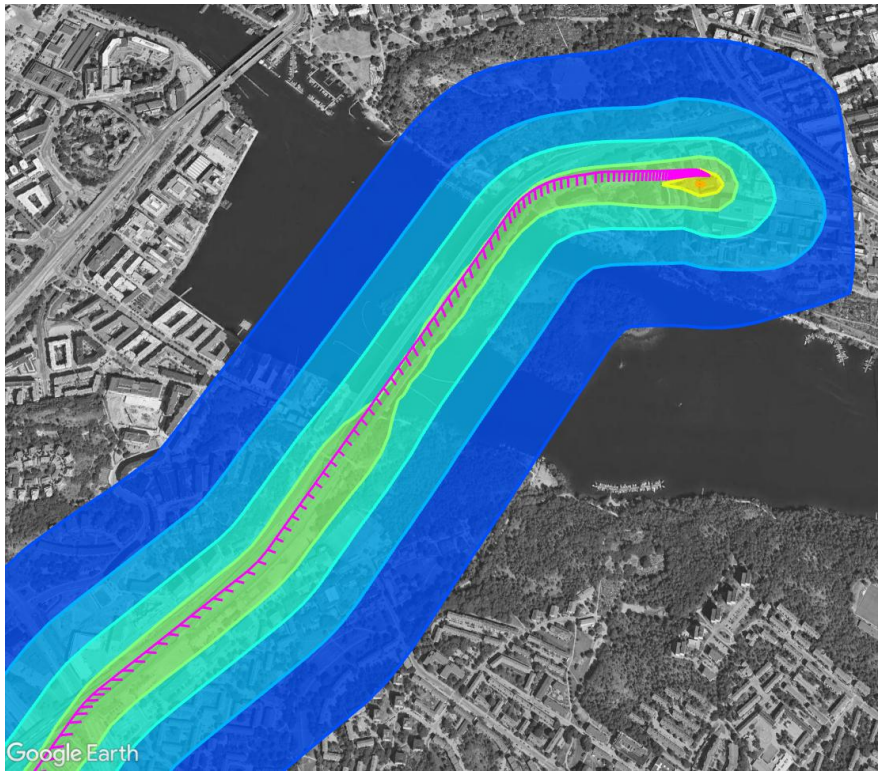
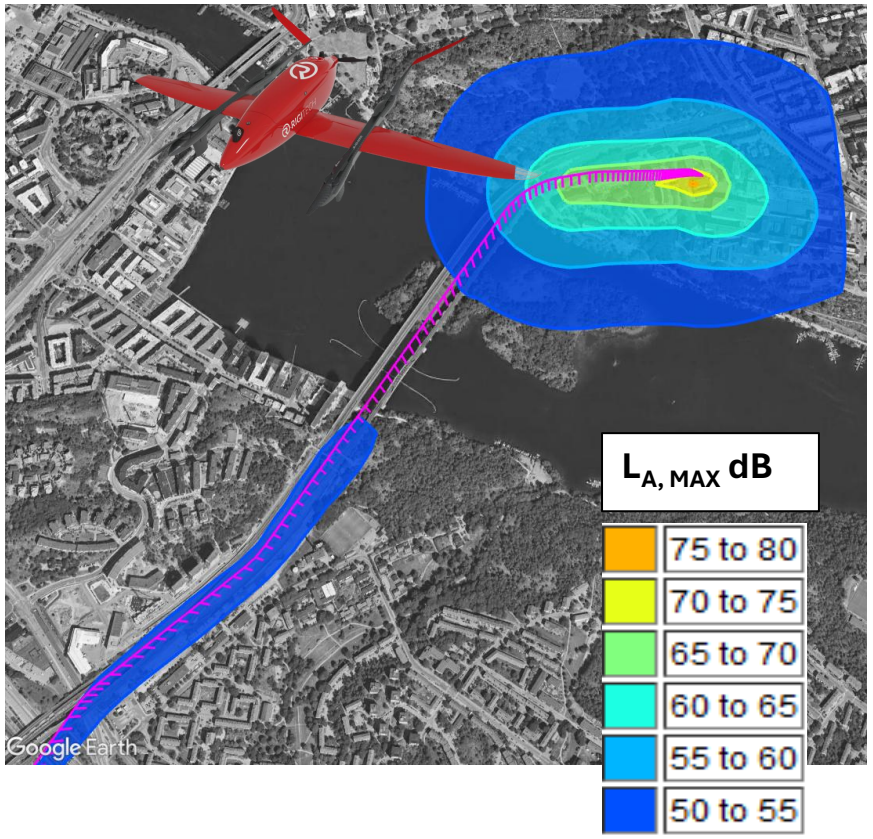


Quadcopter mode the entire way



Transition to wing mode.



Conclusions

- Fixed wing UAV at 50 m above ground:
  - ✓ wing mode operation fairly quiet: $L_{A,max}$ ~45-55 dBA
  - ✓ quadcopter mode : $L_{A,max}$ ~ 70 dBA
- Air traffic noise regulation: The Swedish reference levels regarding $L_{A,max}$ at building facades will govern compliance rather than L_{DEN} levels (energy summation based).
- Using measured data from a state-of-the-art delivery drone, the present $L_{A,max}$ air traffic reference levels at building facades will be met if the droneport is placed at least 50 m from adjacent buildings.
- In view of the tonal character of drone noise, it is anticipated that future UAV reference values may be lowered in relation to those for standard aircraft to reflect the greater annoyance perceived by drones (Gwak et al 2020).

Gwak et al. Sound quality factors influencing annoyance from hovering UAV. *J. Sound Vib.* **2020**, *489*, 115651

Utblick och reflektion

- UAV trafik kommer att öka
- Lägre flyghöjd än dagens flyg – dagens flyg bullerreglerat endast vid start/landning
- Svenska riktvärden för ”störande” buller från UAV saknas ännu:

❑ Även om ljudnivåerna från en flygande drönare i sig inte är höga i relation till andra bullerkällor, kan **subjektiva reaktioner kopplade till bullerhändelsen**, som överraskningsmoment, okänd ljudkaraktär, position ovanför, …, starkt påverka upplevelsen

❑ Ett brett spann av farkoster vad gäller storlek och ljudkaraktär

EASA Open Category - Low Risk - Civil Drones <25 kg
Class: C0 < 250g, C1< 900g, C2 <4kg, C3,C4 <25 kg

Katla 40kg nyttolast 15 kg (länk till Katla Aero och bild)

Joby eVTOL – level flight (länk till Joby och bild)

Extra material

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Remark on noise and innovation

How to increase chances of successful integration in an urban environment:

- Don't introduce surprises, stick to your promises, grow wisely and in agreement
- Be proactive with actions and explain noise levels from restrictions and measurements. Educate residents in acoustics, simulate quantity and quality, number of movements and share "noise forecasts".
- Cooperate with the city and the region, follow processes for neighbourhood collaboration, prepare environmental case for new facilities, be prepared for appeals and possibly trials, listen and communicate.

Calculated sound maps can be used as decision support and to explain planning work to minimize disturbances

Aircraft noise metrics:

- Day-evening-night level. L_{DEN}
- Flygbullernivå, FBN

$$\mathbf{L_{DEN}} = 10log_{10}\left(\frac{1}{24}\left(12 \times 10^{\frac{\mathbf{L_{day}}}{10}} + 4 \times 10^{\frac{\mathbf{L_{evening}+5}}{10}} + 8 \times 10^{\frac{\mathbf{L_{night}+10}}{10}}\right)\right)$$

$\mathbf{L_{day}}$: $\mathbf{L_{eq}}$ for 07:00 - 19:00 (12 hours)
$\mathbf{L_{evening}}$: $\mathbf{L_{eq}}$ for 19:00 - 23:00* (4 hours)
$\mathbf{L_{night}}$: $\mathbf{L_{eq}}$ for 23:00* - 07:00 (8 hours)

FBN – Flyg Buller Nivå (Flight Noise Level) is a Swedish metric corresponding to L_{den}

Part of day	Hours*	Penalty (dB) L_{den}	Penalty (dB) FBN
day	07:00 - 19:00	0 dB	0
evening	19:00 - 23:00	5 dB	10×log10(3)≈4.8 dB
night	23:00 - 07:00	10 dB	10×log10(10)=10 dB

*) different time period limits in different countries.
In Sweden: 6:00, 18:00, 22:00 for calculation of FBN

Parameters affecting noise exposure

- *UAV design parameters: lay-out, rotor rpm and pitch*
- *Operational modes*: lift, hover, free flight
- *Flight data/Trajectory*:
  - Groundtrack – via way points in Google Earth
  - Profile – altitude, speed
- *Population density:* SCB data
- *Screening,* e.g. from buildings (shadow zones)
- *Facade insulation* (interior noise)

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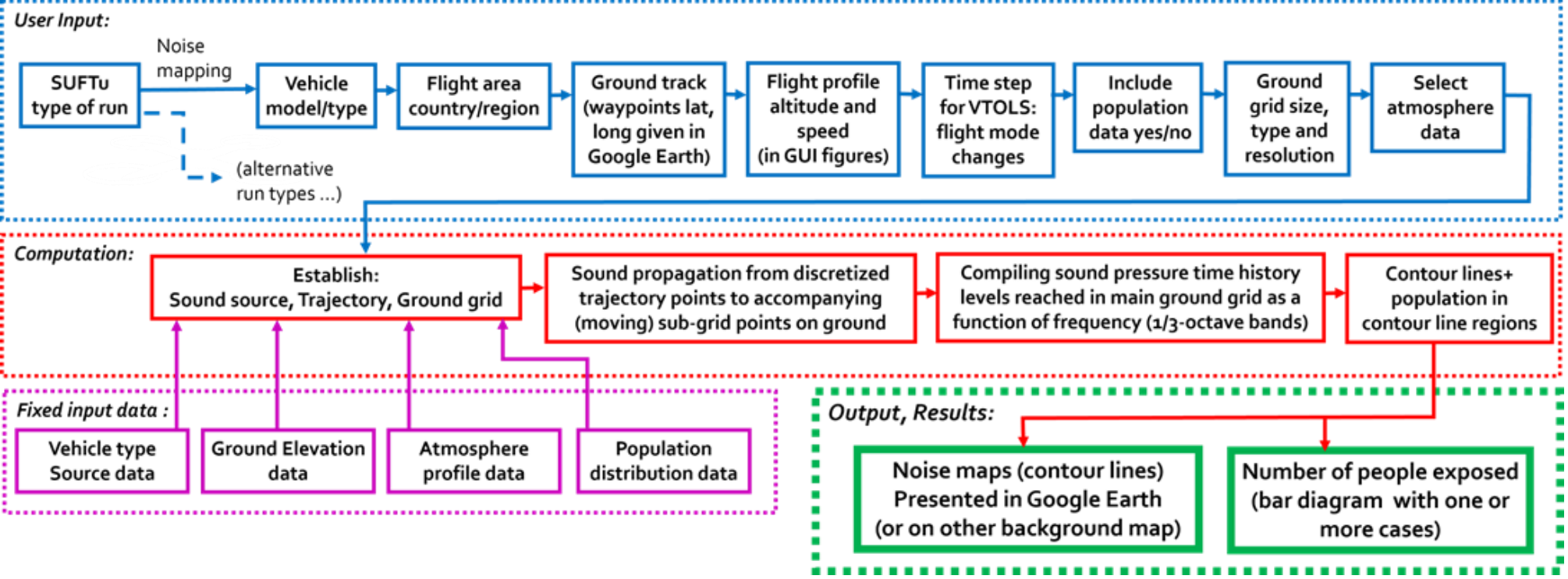


Figure 2. Process flow chart for running SAFTu to produce noise maps from a given UAV flight. From the SAFTu manual (Tengzelius et al 2025).

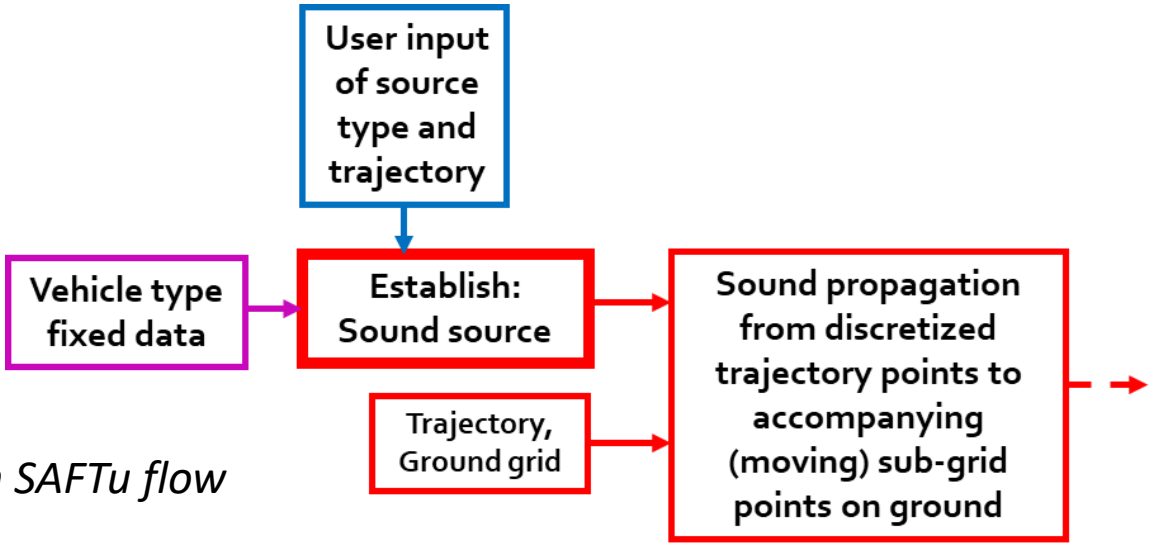


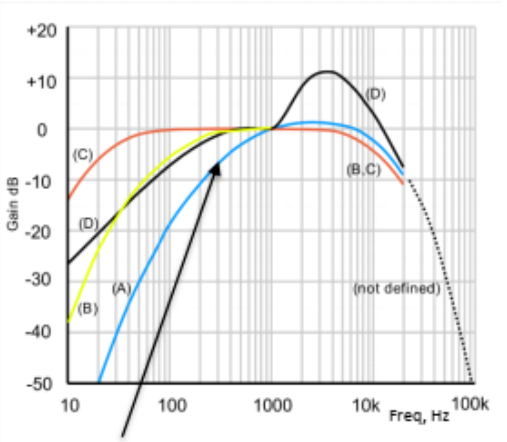
Figure 5 Vehicle sound source representation in SAFTu flow chart logics

SAFTu functionality list

SAFTu functionality	Status
Sound Soures/Vehicles - simplified multicopters, "small" and d:o VTOL-taxi	√
Flight mode and rpm-dependent sound sources including directivity	ongoing
Noise mapping, contours and *time history spectra in any receiving point and metric*	√
Atmospheric data import and profile implementation: Nordic countries	√
Topographic data worldwide (NOTE: atmospheric data simple ISA outside Nordic countries)	√
Topography (buildings) impact on ground noise – topography "simple", buildings ...	ongoing
Delta dB contours (L_{Amax} or "any" metric) - generality trajectory	ongoing
Refractive raytracing - incl. algorithm for wind turbulence dep. diffraction into "shadow" zones	coming
Noise mapping, contours and *time history spectra in any receiving point and metric*	√
UAM scenarios: $L_{A,den\ (FBN)}$ contours – realistic scenarios, gridding methodology	? needs
Synthesis with existing ground traffic noise data. Evaluation of “added” noise impact	APIS II?

EASA: Guidelines for measuring noise from UAVs

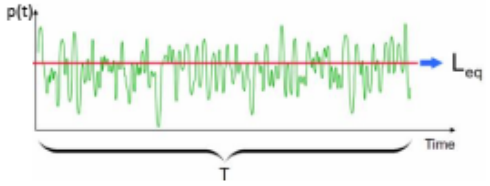
Noise metrics

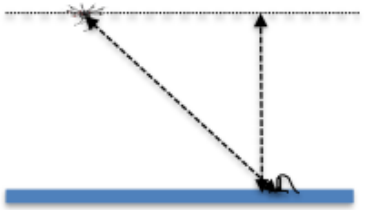


A-frequency weighting: best compromise between UAS annoyance and available equipment.

For the **Hover** procedure, L_{eq} will be the A-weighted noise level averaged over 30 seconds.

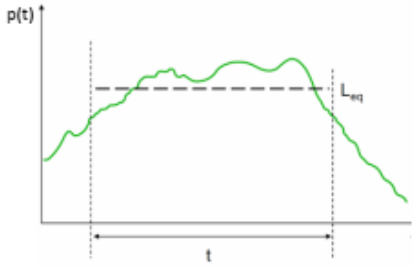
$$L_{eq} = 10 \log_{10} \frac{1}{T} \int_0^T \left(\frac{p(t)}{p_0} \right)^2 dt$$





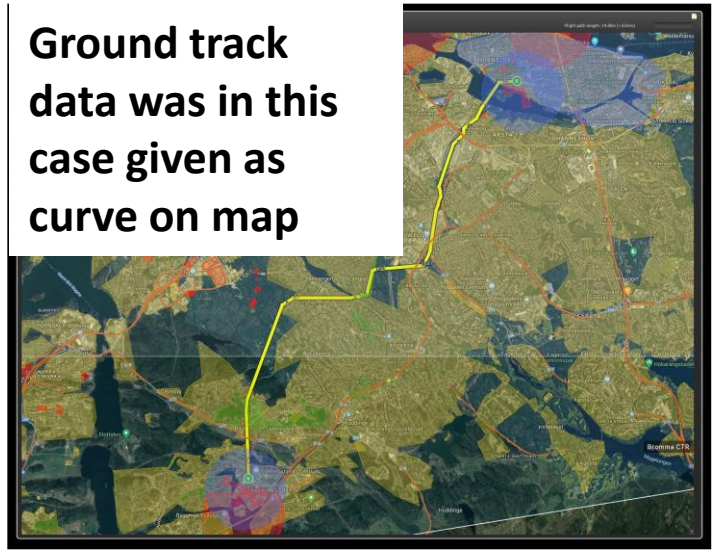
For the **Level-Flight** procedure, SEL ("Sound Exposure Level") will be the A-weighted noise integrated over time.

$$SEL = L_{eq} + 10 \log \left(\frac{t}{1s} \right)$$

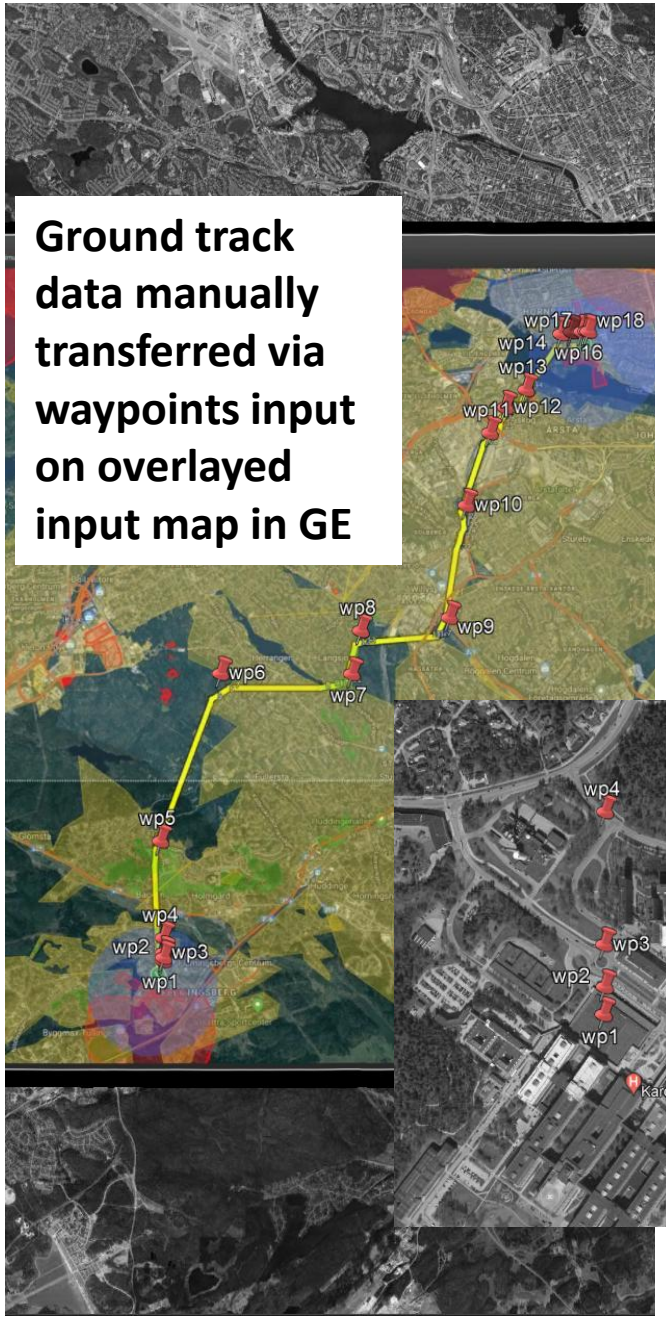


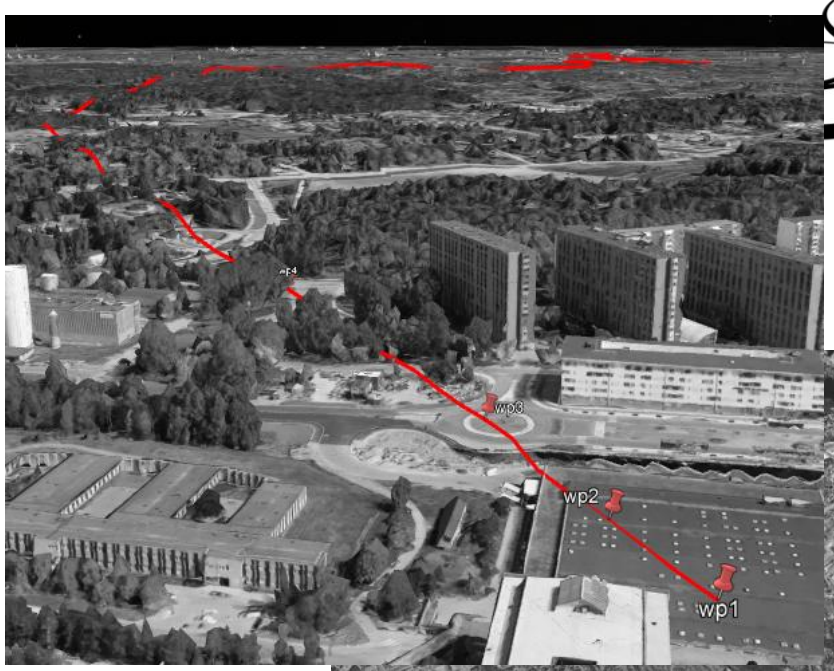
EASA

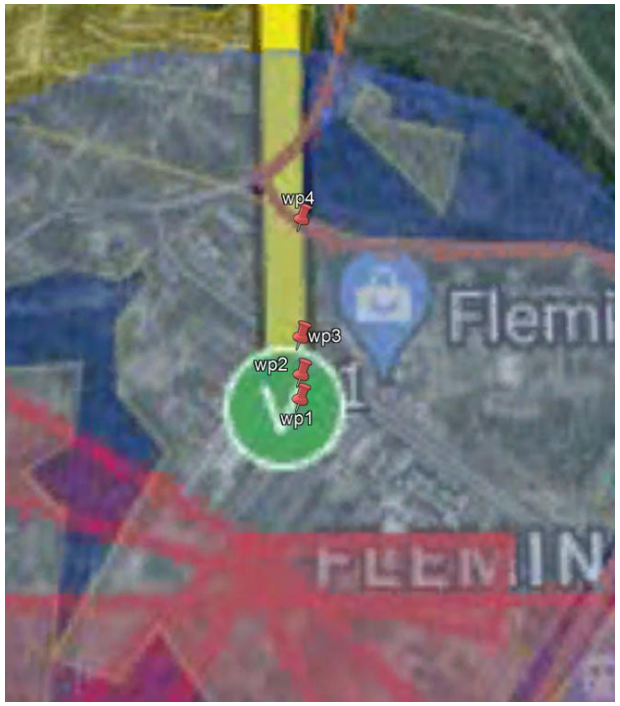
Ground track data was in this case given as curve on map

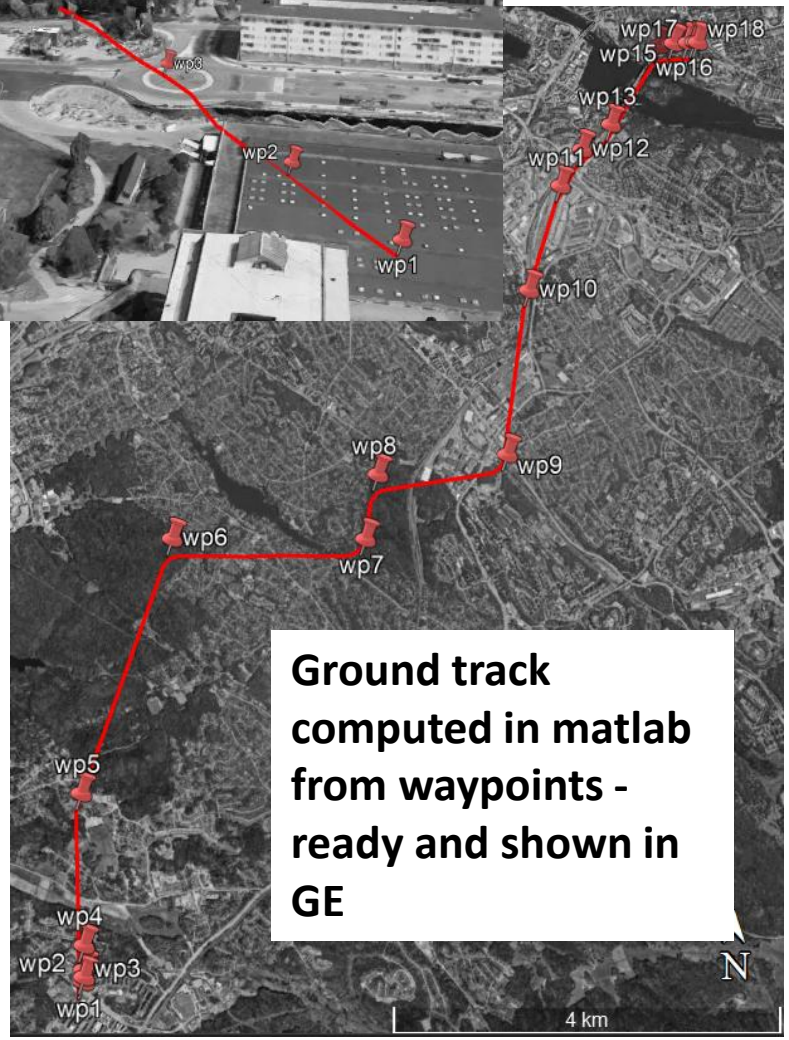


Ground track data manually transferred via waypoints input on overlayed input map in GE

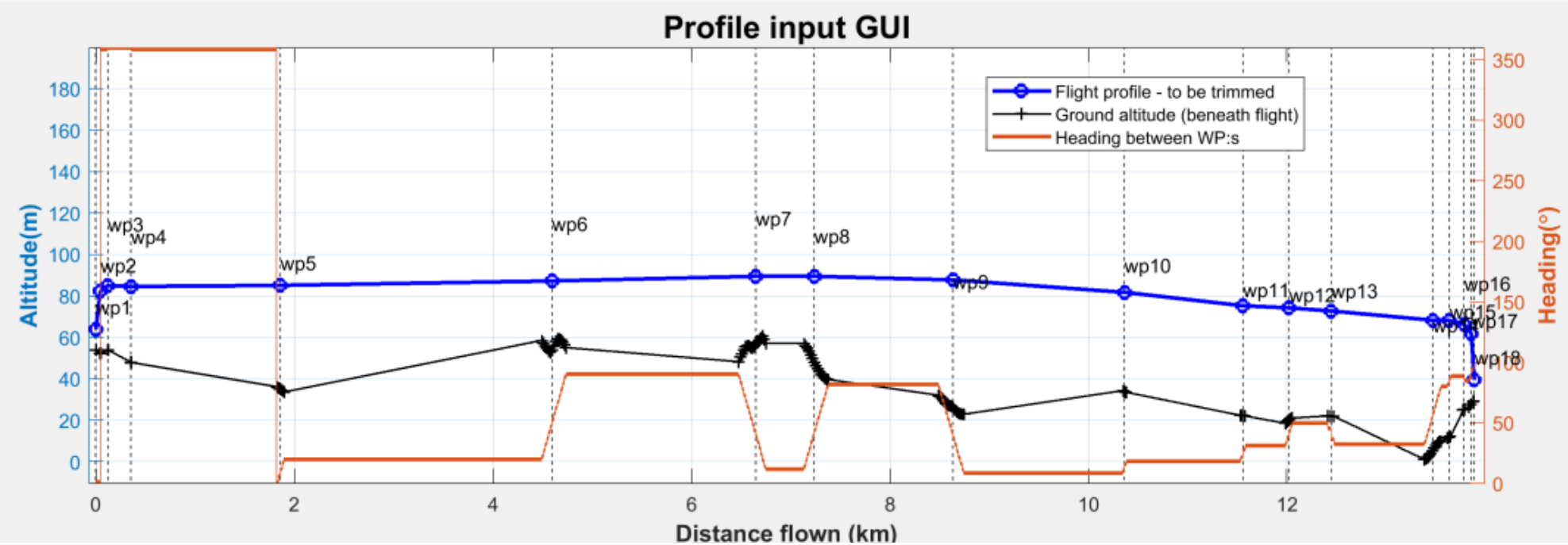




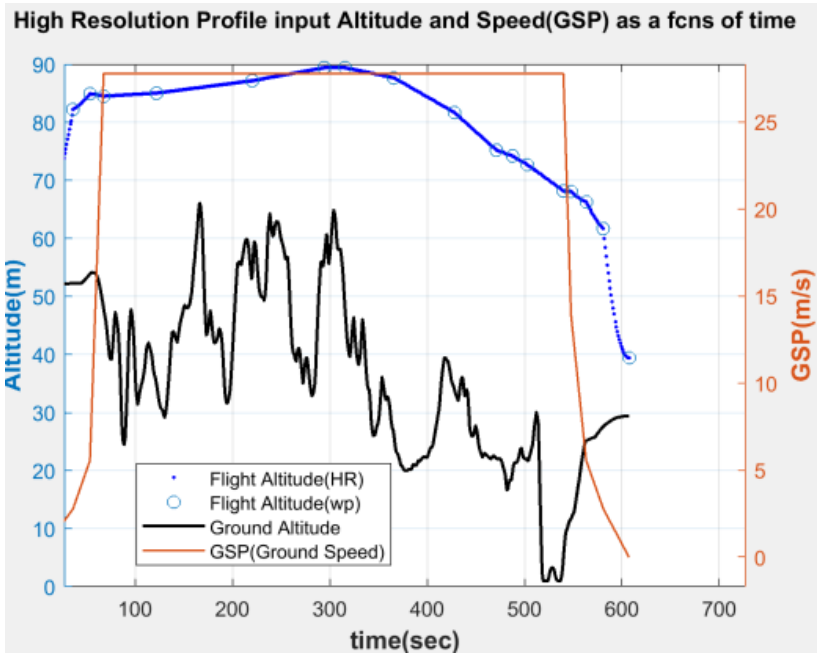


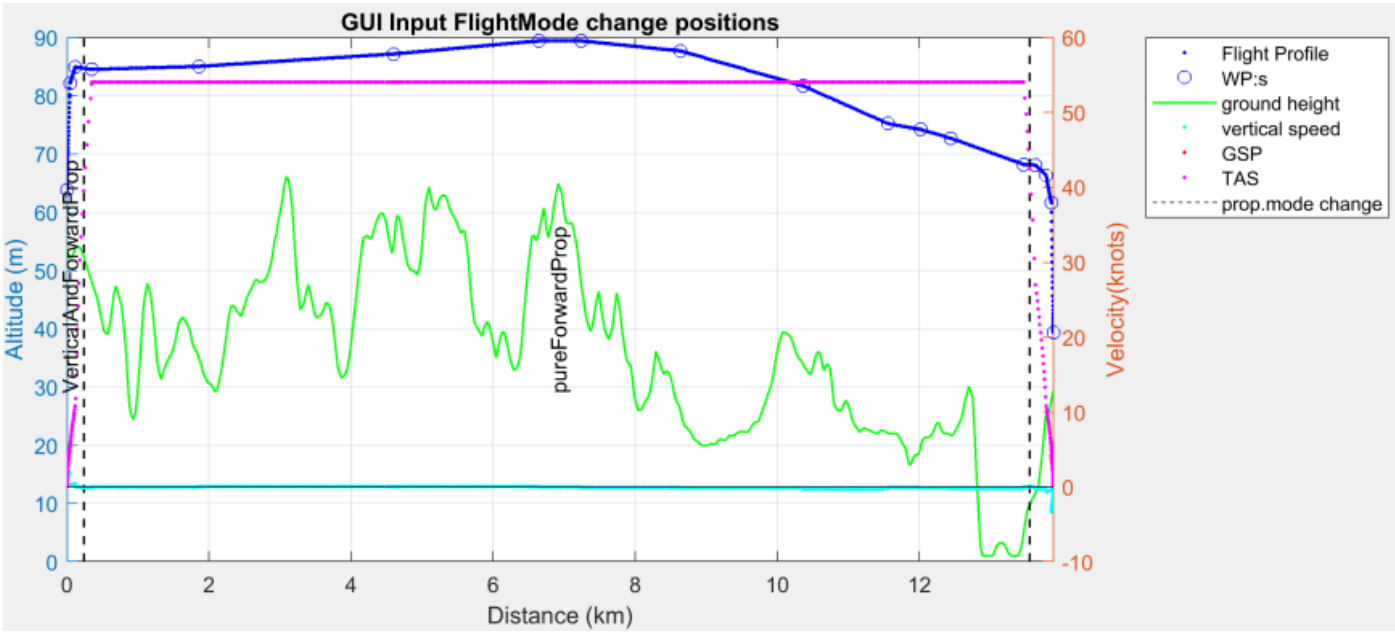


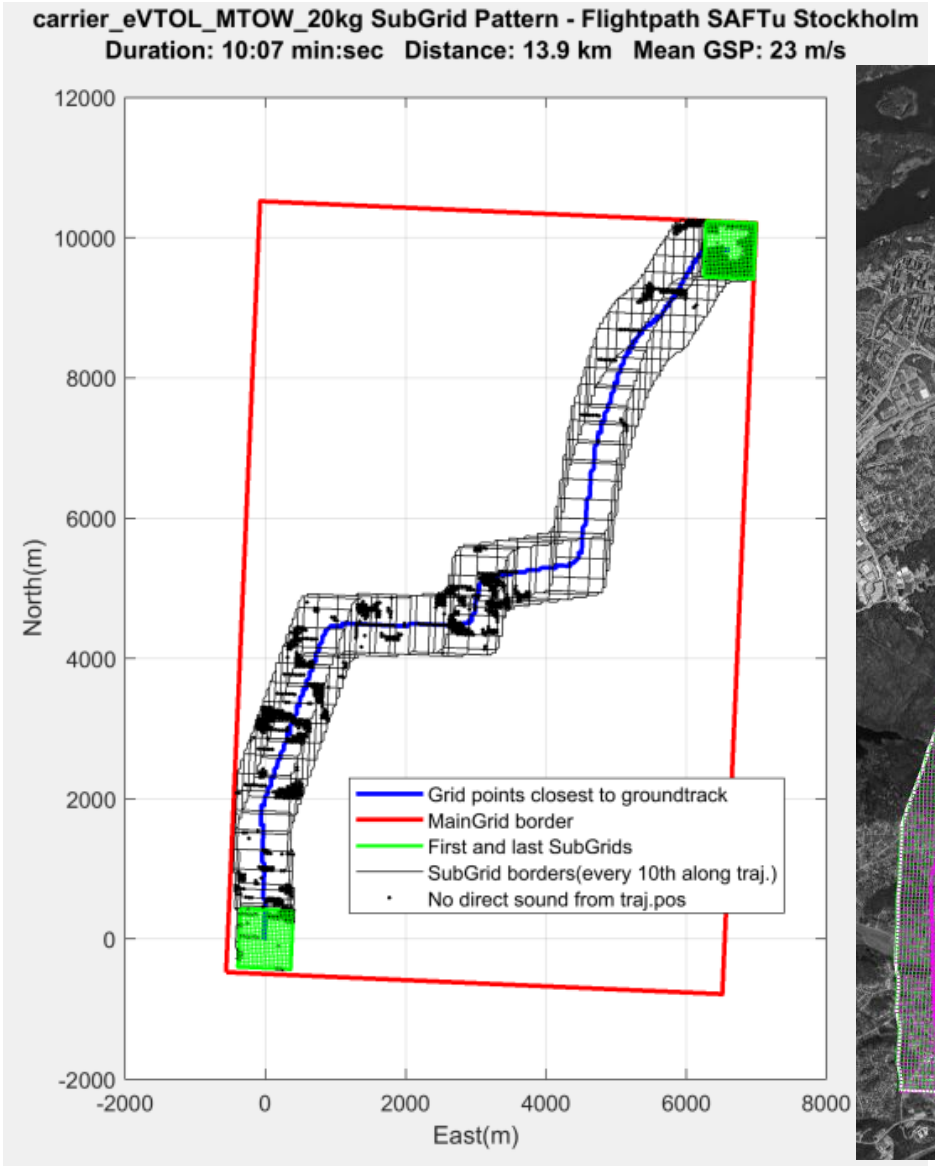
Ground track computed in matlab from waypoints - ready and shown in GE

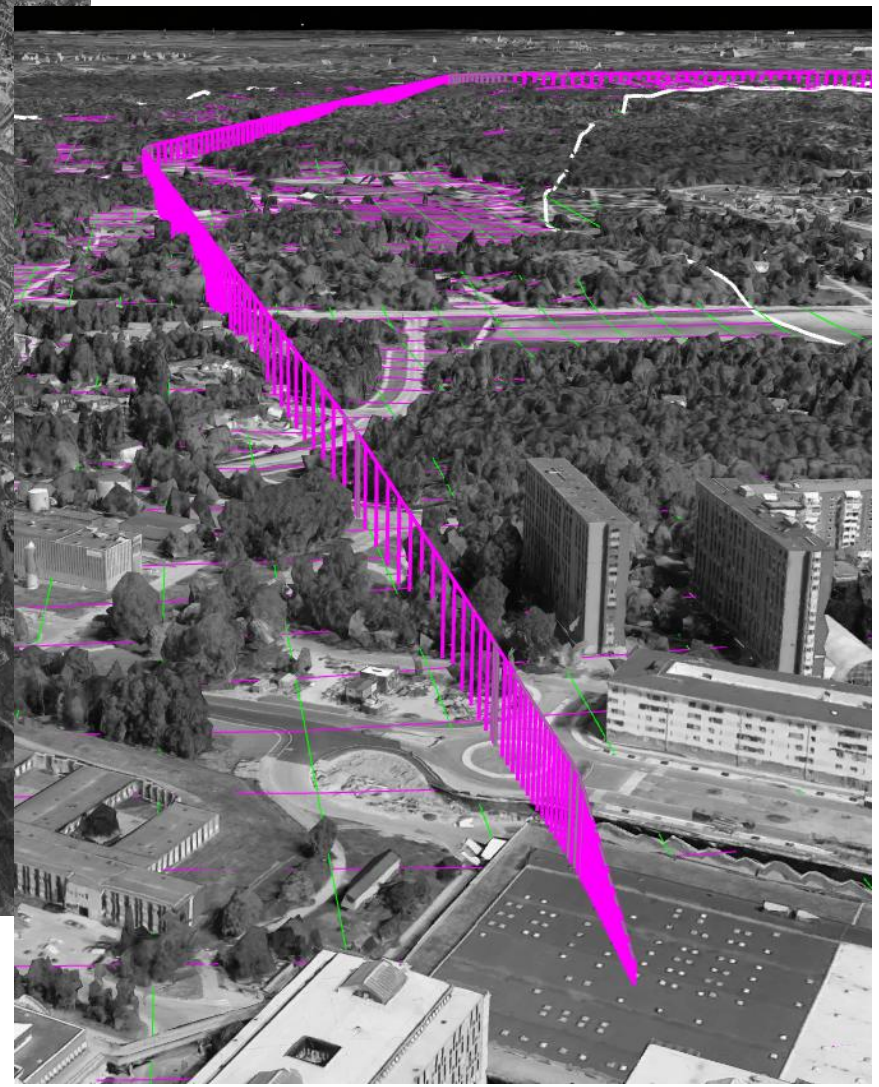


Profile x, y and speed + Flight mode changes input









Ground receiving grid and trajectory established
(topography data in this case without buildings)

Task 4.1: UAV Annoyance rating

1. Schäfer et al 2021: A total of 24 studies included in systematic review on noise emissions of drones.

2. Conclusion I: The literature of drone noise effects on humans is still very scarce. Nevertheless, the current literature provides a fairly consistent picture, suggesting that drone noise is substantially more annoying than road traffic or aircraft noise due to special acoustic characteristics, in particularly pure tones and high-frequency broadband noise.

3. Conclusion II: The increased annoyance to drone noise could be accounted for with level corrections (or, alternatively, stricter limit values for drone noise in environmental guidelines/legislation). However, currently available studies do not allow reliably defining such correction terms.

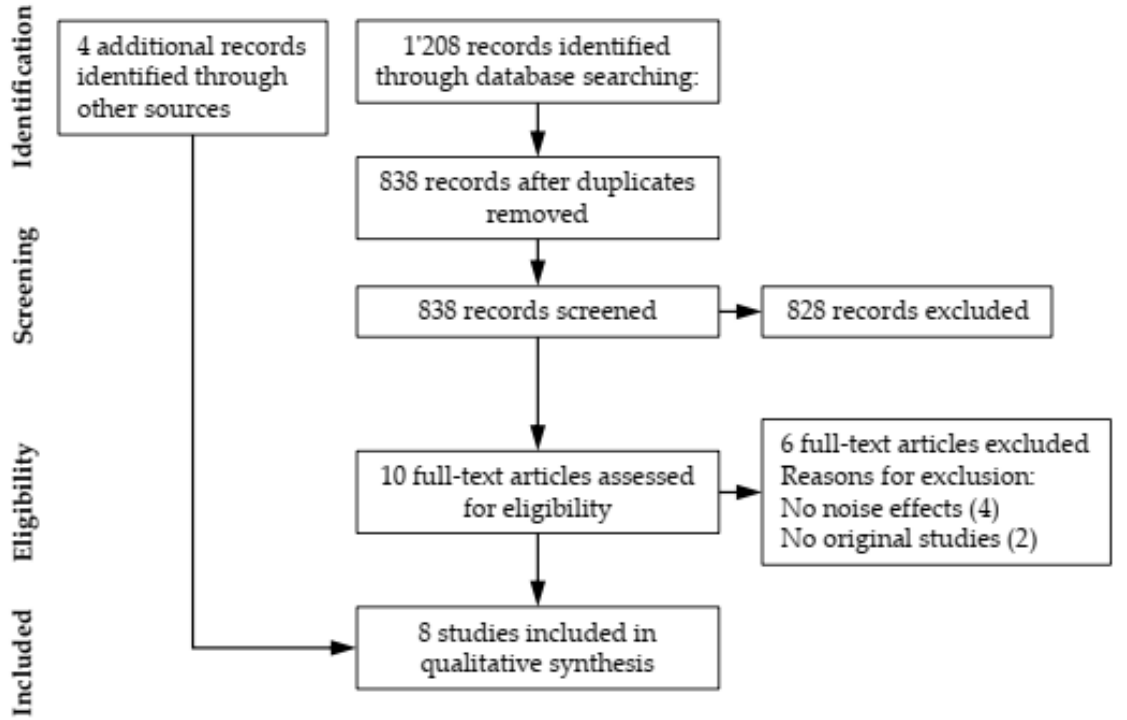


Figure 2. PRISMA flow diagram of the systematic review on noise effects of drones.

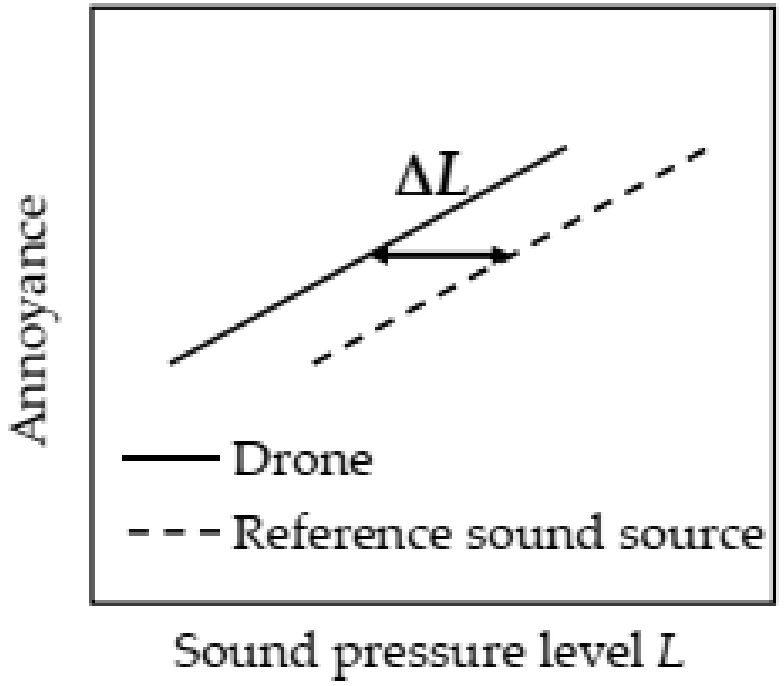
Beat Schäffer et al 2021. Drone Noise Emission Characteristics and Noise Effects on Humans—A Systematic Review , International Journal of *Environmental Research and Public Health*

Task 4.1: Annoyance from drones

Annoyance rating by comparing drone noise to road traffic or standard aviation noise

Example: Gwak et al . Sound quality factors influencing annoyance from hovering UAV. *J. Sound Vib.* **2020**, *489*, 115651 :

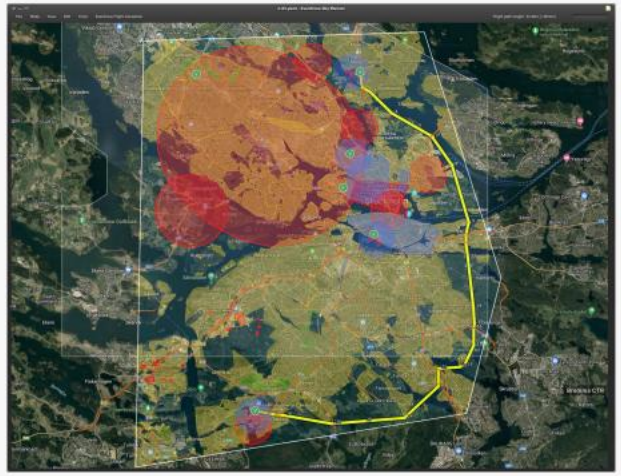
ΔL_{Aeq} ~10 dB
(large drone vs. aircraft);
ΔL_{Aeq} ~6 dB
(large vs. small drone);
ΔL_{Aeq} ~4 dB
(small drone vs. aircraft)



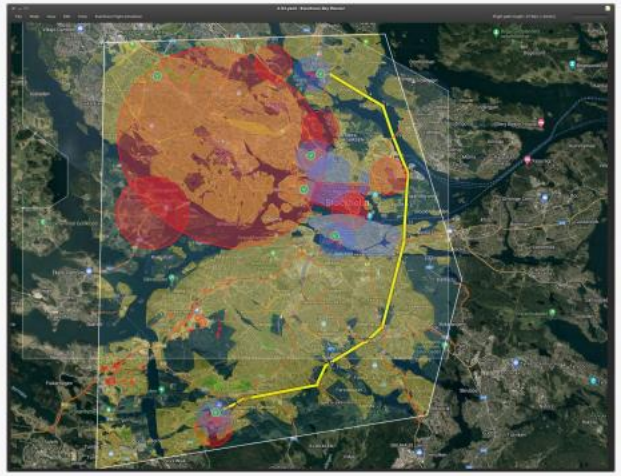
Beat Schäffer et al 2021. Drone Noise Emission Characteristics and Noise Effects on Humans—A Systematic Review , International Journal of *Environmental Research and Public Health*, ***2021,*** *18,5940*

Example of delivery use-case scenario (between stockholm hospitals)

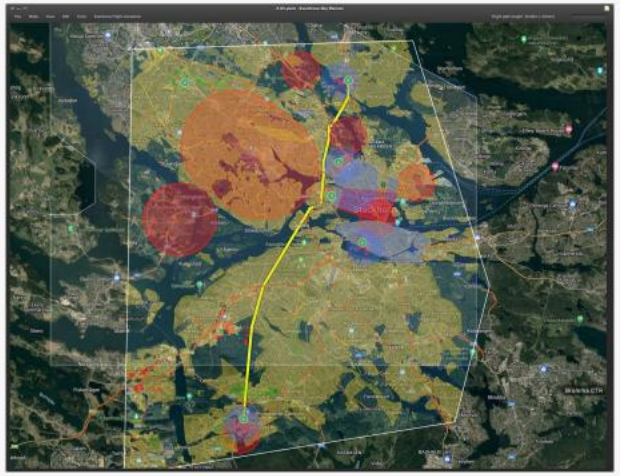
Rutt 1: Danderyds sjukhus (H) – Huddinge sjukhus (H)



Scenario 1: *32,4 km – 19 min 0 sek*



Scenario 2: *27,5 km – 16 min 17 sek*



Scenario 3: *20,5 km – 12 min 23 sek*

Färgkodning: GUL=Befolkat område, BLÅ=Tätbefolkat område eller flygförbudszon som kräver koordinering, RÖTT=Flygförbudszon.
Flygtid: Drönare med marschfart 30 m/s plus 1 min vid start/landning.
Scenario 1: Lägre markrisk, SAIL 2-drönare, längre flygsträcka, dagens luftrum. Endast rutt 1, 3 och 7 möjliga.
Scenario 2: Högre markrisk, SAIL 3- eller 4-drönare, kortare flygsträcka, dagens luftrum. Endast rutt 1, 3 och 7 möjliga.
Scenario 3: Högre markrisk, SAIL 4-drönare, kortare flygsträcka, spekulativt framtida luftrum. Samtliga rutter möjliga.