DTU

DOI: 10.5281/zenodo.3476763

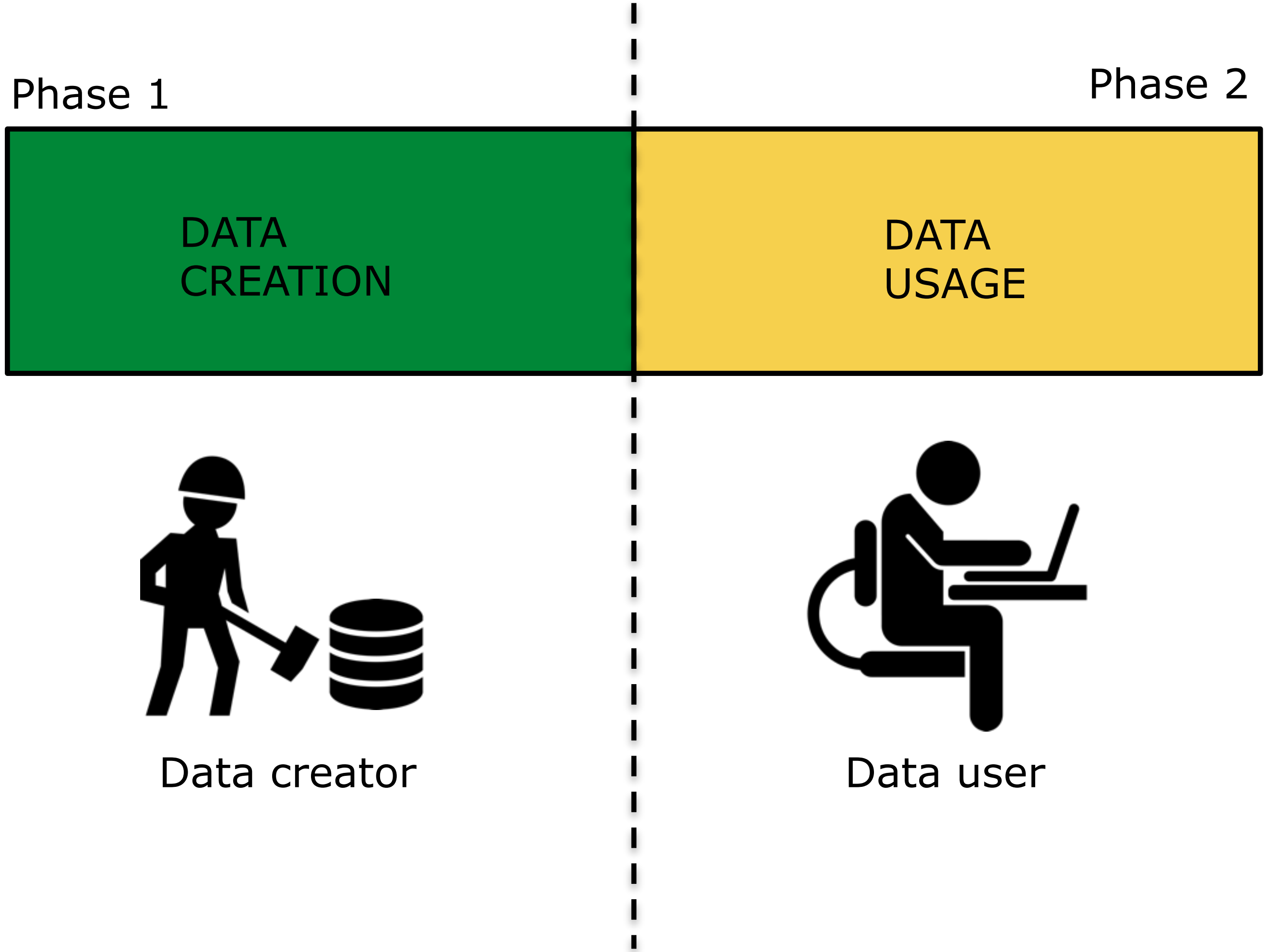
DTU

Nikola Vasiljevic

Wind Lidar Digitalization

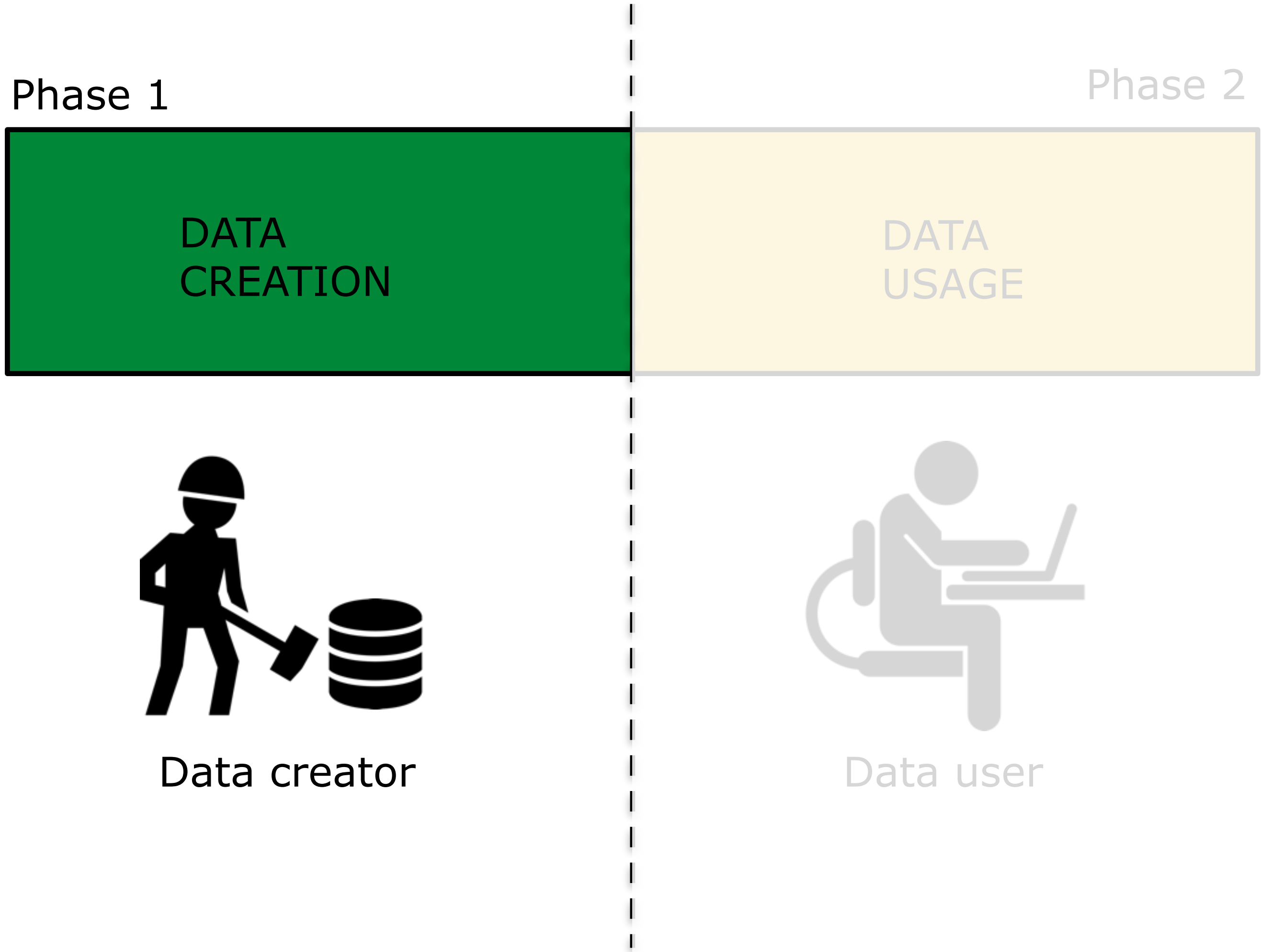
NREL, 8th October 2019

Simplistic overview of (research) projects



Graphics designed using FlatIcon.com

Simplistic overview of (research) projects



Graphics designed using FlatIcon.com

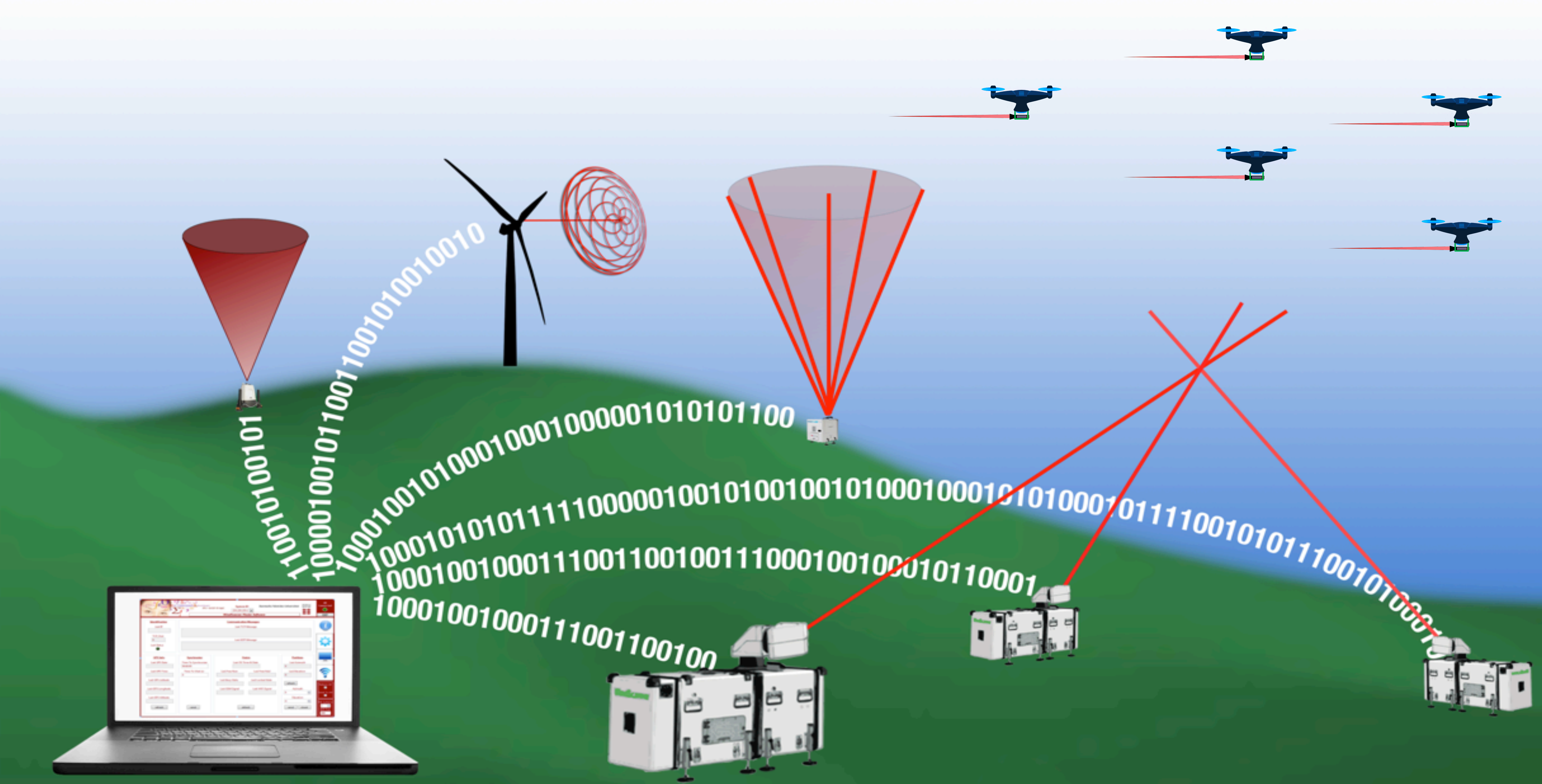
Digitalization

Digitalization most often refers to enabling, improving and/or transforming business operations and/or business functions and/or business models/processes and/or activities, by leveraging digital technologies and a broader use and context of **digitized data**, turned into **actionable knowledge** with a specific benefit in mind [1].

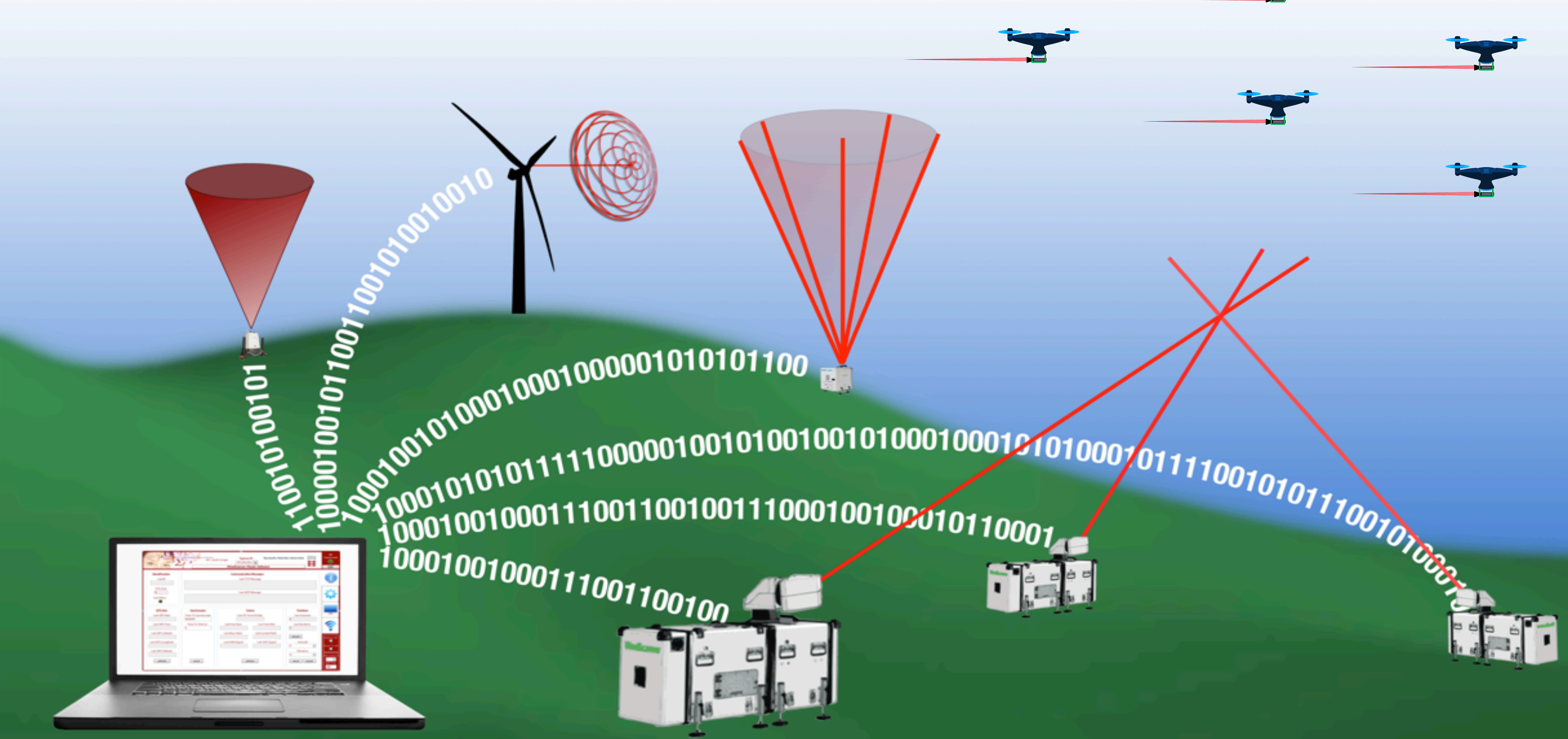
It requires digitization of information but it means more and at the very center of it is data.

[1] https://www.i-scoop.eu/digitization-digitalization-digital-transformation-disruption/

Unprecedented insight into the wind conditions



Unprecedented insight into the wind conditions
...but at what cost?



Challenge

There is a need to make the (lidar) technology “dummy-proof” for the larger audience, but also quite “open” for power users. [2]

[2] https://zenodo.org/record/1146326

Challenge continued

- How to create **TeraBytes** of affordable and high-quality data?
- How to make **TeraBytes** of data usable?

Challenge still continued

- How can we eliminate a need for lidar ‘experts’ ?

Lidar
expert

Image source: flaticon.com

Challenge still continued

- How can we eliminate a need for lidar ‘experts’ ?

Lidar
expert

e - WindLidar

OpenLidar

Image source: flaticon.com

e-WindLidar initiative

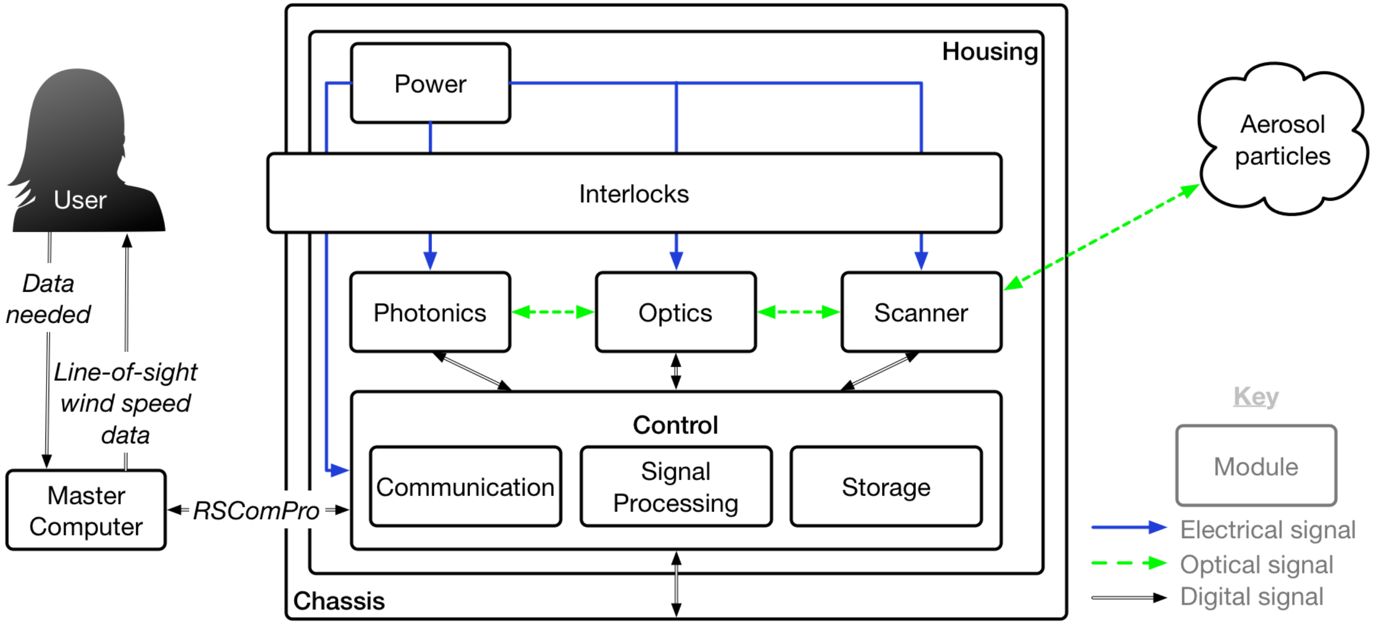
- Develop community-based tools that will simplify:
  - Planning and configuration of lidar-based field campaigns
  - Operation of lidars in field campaigns
  - Usage of lidar data

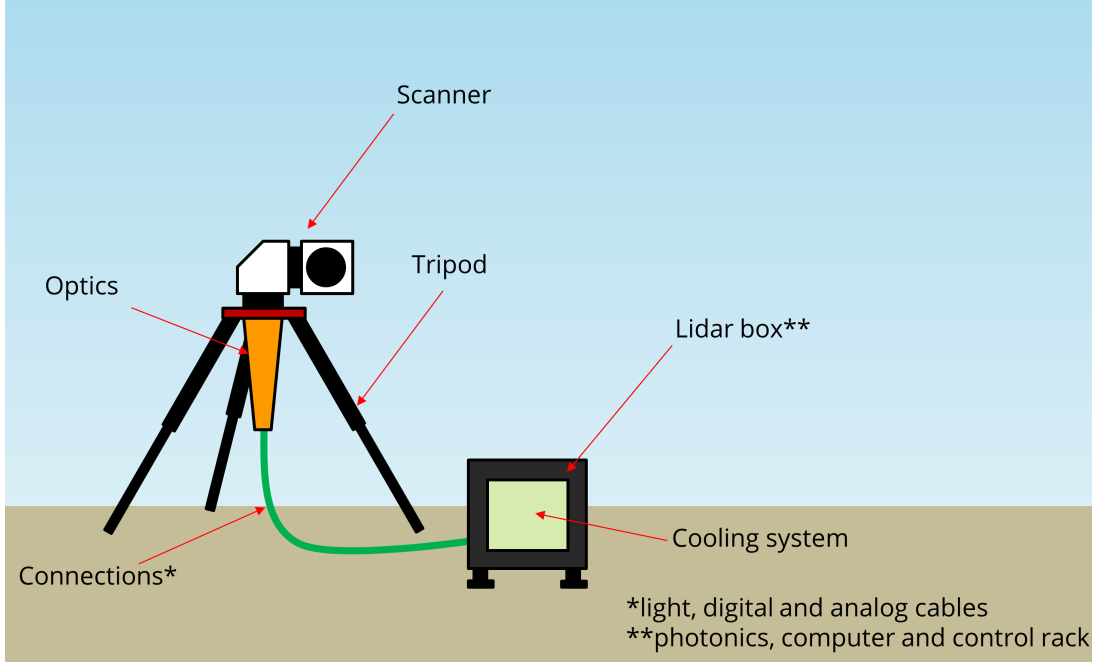
- e-WindLidar idea was conceived during the WindScanner.EU project under the name WindScanner Information System [3]

[3] https://zenodo.org/record/1175211

OpenLidar initiative

- Development of a modular wind lidar architecture [3, 4]
- Providing a framework for cooperation





[3] https://zenodo.org/record/3414197
[4] https://www.openlidar.net/

DTU contributions to e-WindLidar initiative

- Led application of FAIR data principles on wind lidar data [5, 6]
- Developed *campaign-planning-tool* – Python package for planning and configuring scanning lidar measurement campaigns [7, 8]
- Developed *YADDUM* (**Y**et **A**nother **D**ual-**D**oppler **U**ncertainty **M**odel) – Python package for calculating dual-Doppler uncertainty [9]
- Developed scanning lidar trajectory generator – Python package

[5] https://zenodo.org/record/2478051
[6] https://github.com/e-WindLidar/Lidaco
[7] https://www.wind-energ-sci-discuss.net/wes-2019-13/
[8] https://github.com/niva83/campaign-planning-tool
[9] https://zenodo.org/record/1441178

e - WindLidar

DTU contributions to e-WindLidar initiative

- Led application of FAIR data principles on wind lidar data [5, 6]
- Developed *campaign-planning-tool* – Python package for planning and configuring scanning lidar measurement campaigns [7, 8]
- Developed *YADDUM* (**Y**et **A**nother **D**ual-**D**oppler **U**ncertainty **M**odel) – Python package for calculating dual-Doppler uncertainty [9]
- Developed scanning lidar trajectory generator – Python package

[5] https://zenodo.org/record/2478051
[6] https://github.com/e-WindLidar/Lidaco
[7] https://www.wind-energ-sci-discuss.net/wes-2019-13/
[8] https://github.com/niva83/campaign-planning-tool
[9] https://zenodo.org/record/1441178

campaign-planning-tool background

- Establish the campaign planning workflow
- **Digitalize** the workflow, thus create a tool
- Make the tool modular
- Base the tool on open source solutions
- Describe the tool
- Make the tool publicly available

Physical lidar expert

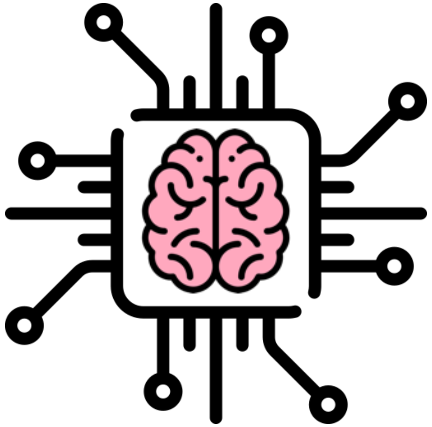
campaign-planning-tool background

- Establish the campaign planning workflow
- **Digitalize** the workflow, thus create a tool
- Make the tool modular
- Base the tool on open source solutions
- Describe the tool
- Make the tool publicly available

Physical lidar expert

campaign-planning-tool background

- Establish the campaign planning workflow
- **Digitalize** the workflow, thus create a tool
- Make the tool modular
- Base the tool on open source solutions
- Describe the tool
- Make the tool publicly available



Digital lidar expert

Workflow Phases

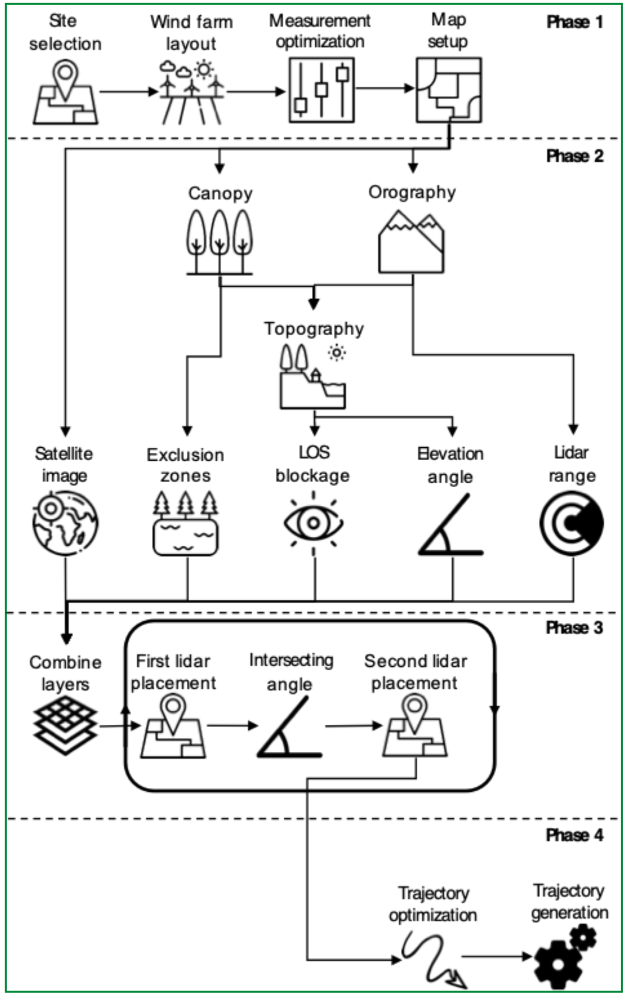


Image source: flaticon.com

DTU

Workflow Phases

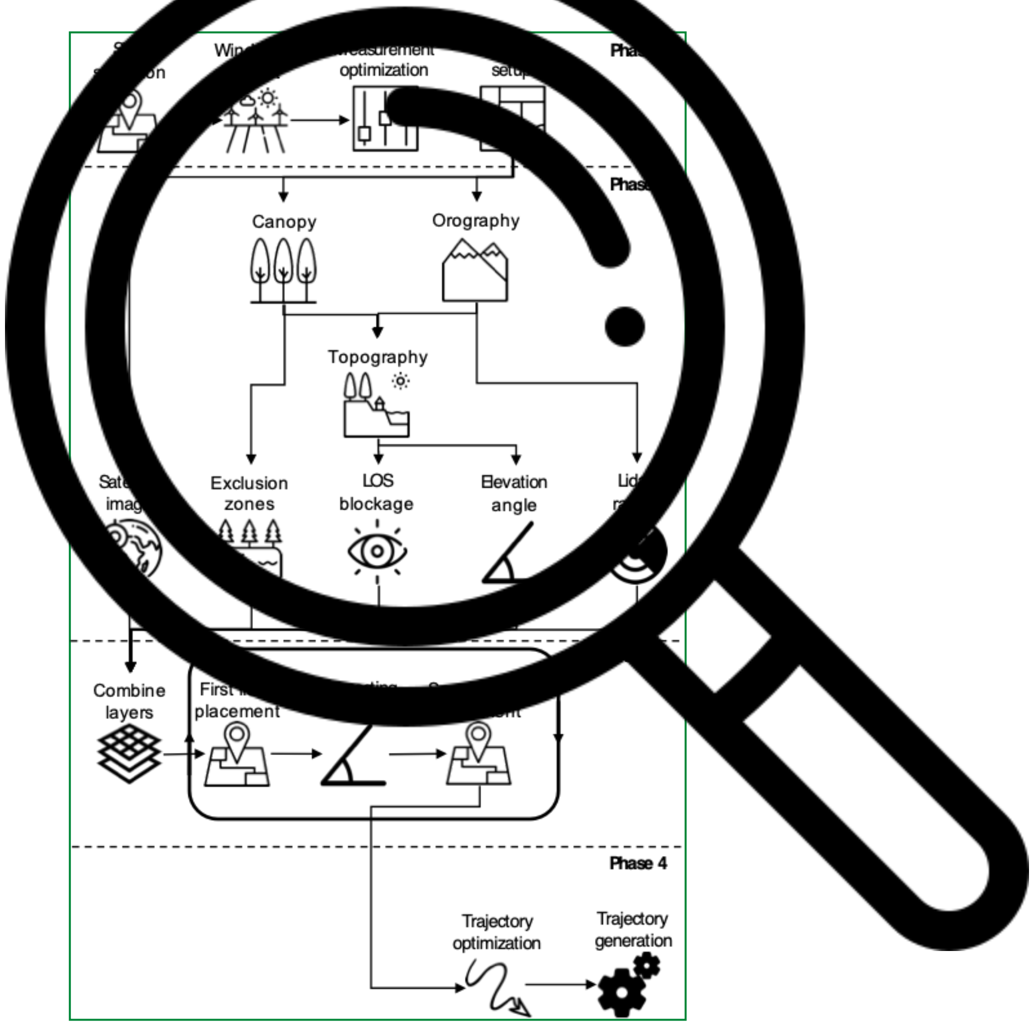
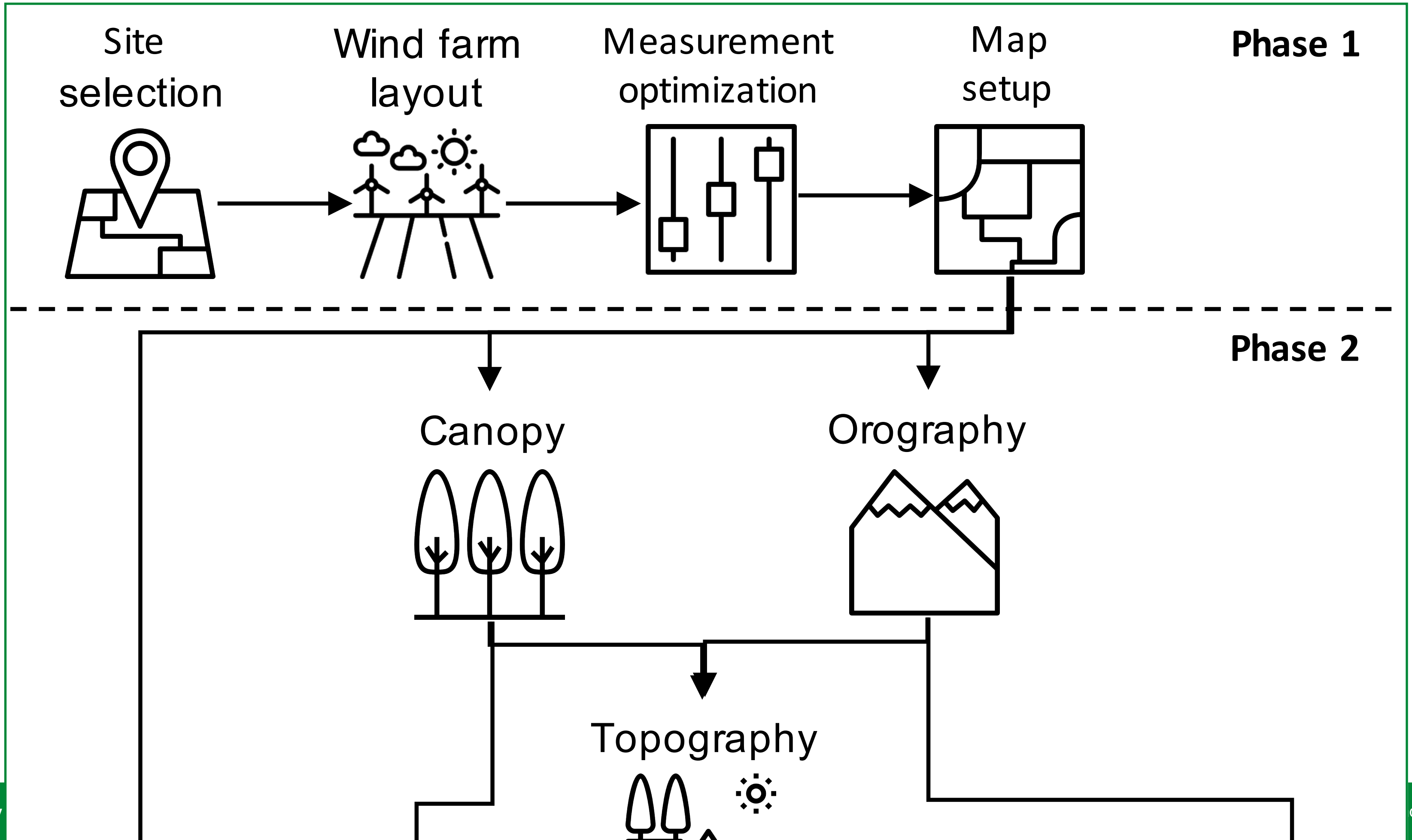
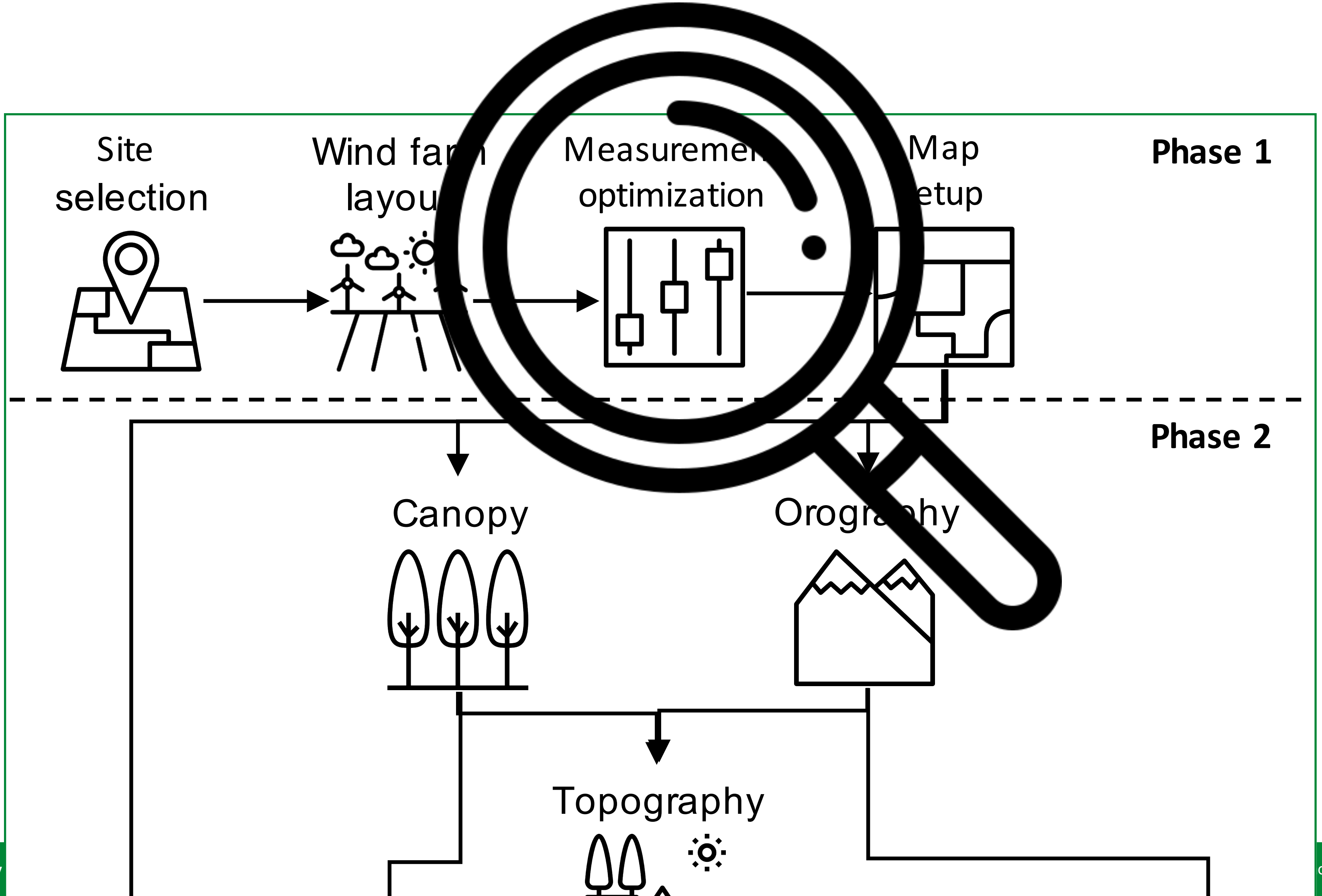


Image source: flaticon.com

Workflow Phases

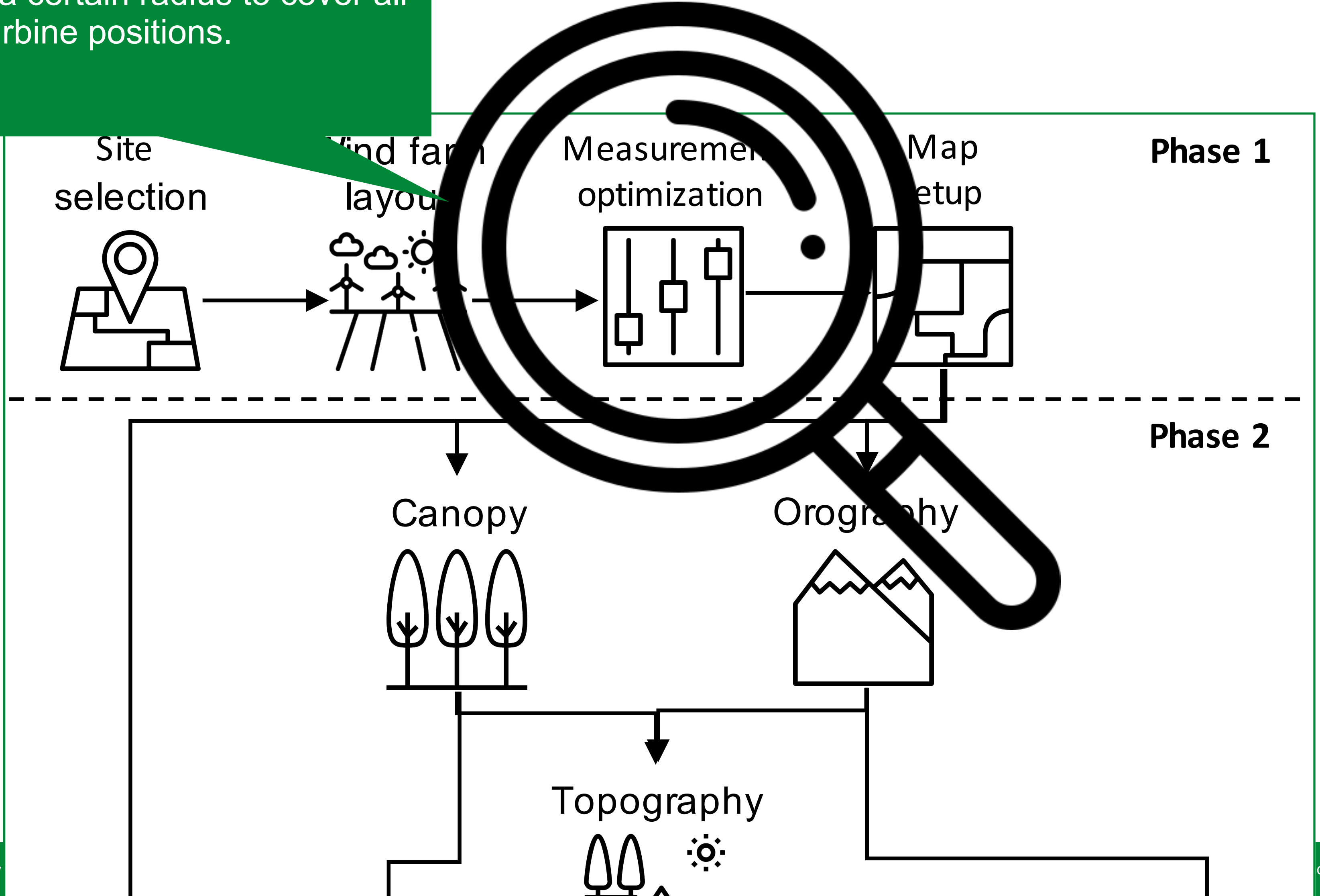


Workflow Phases

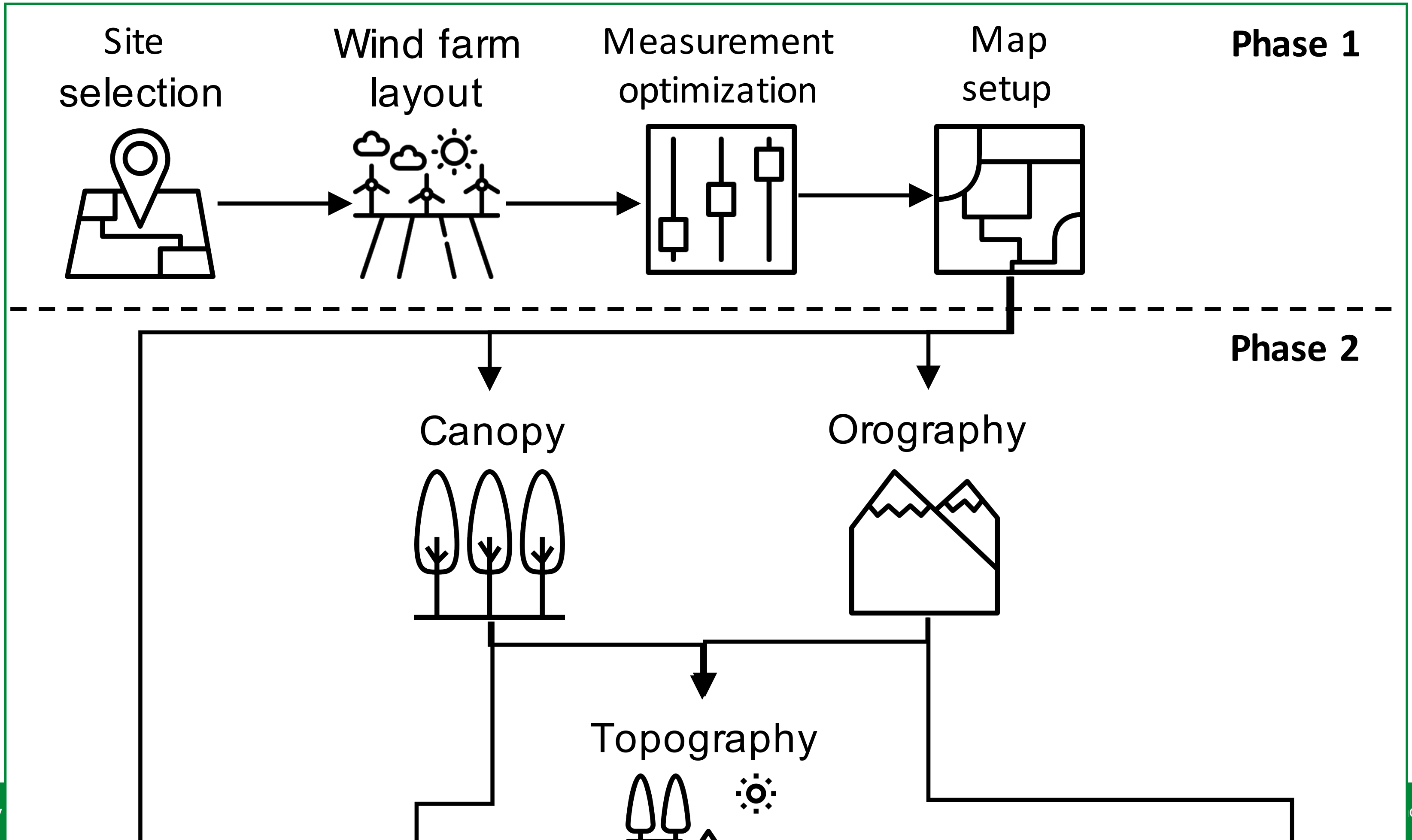


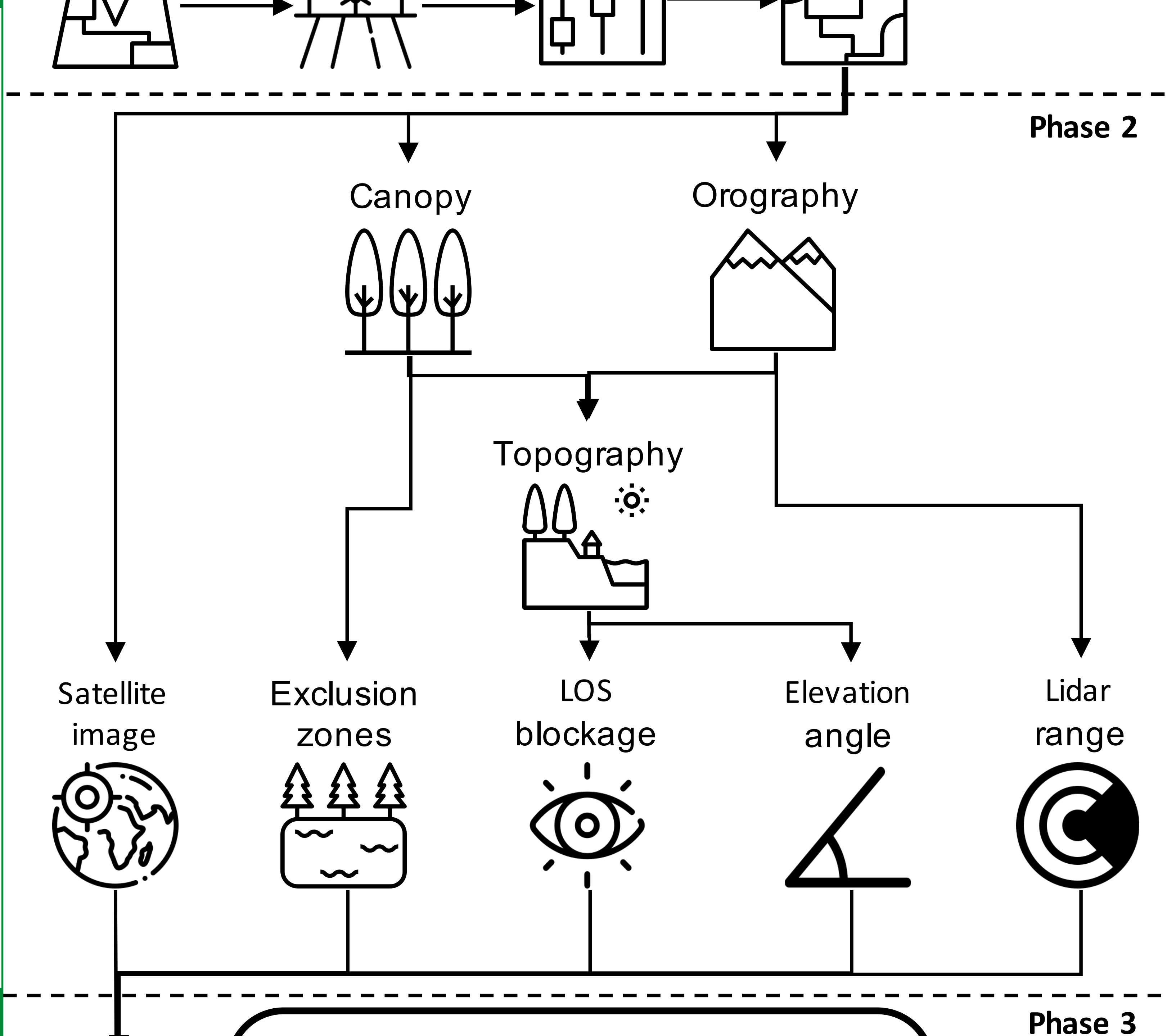
Solving **disc covering problem** in which we are searching for a minimum number of disks with a certain radius to cover all turbine positions.

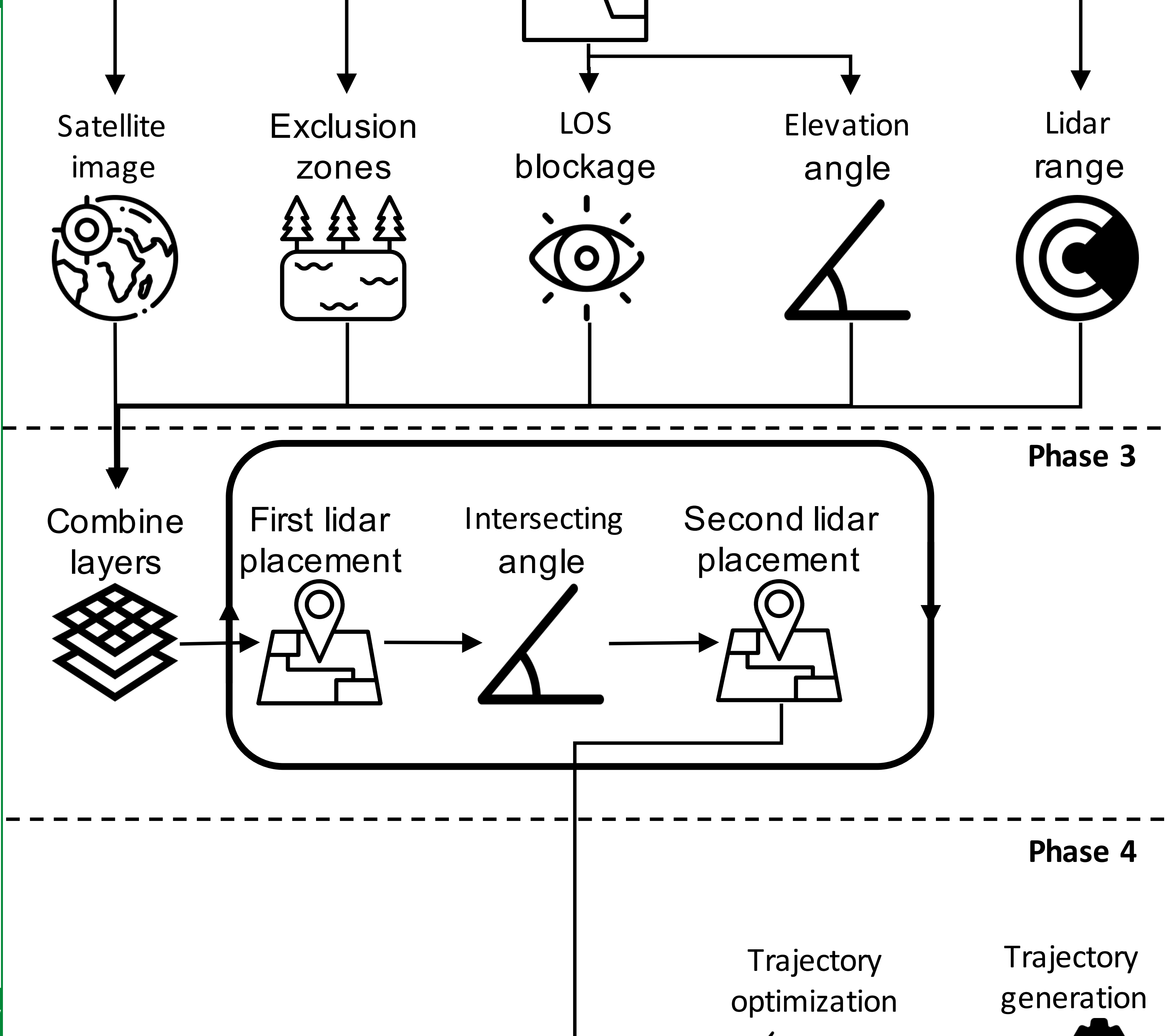
Workflow Phases

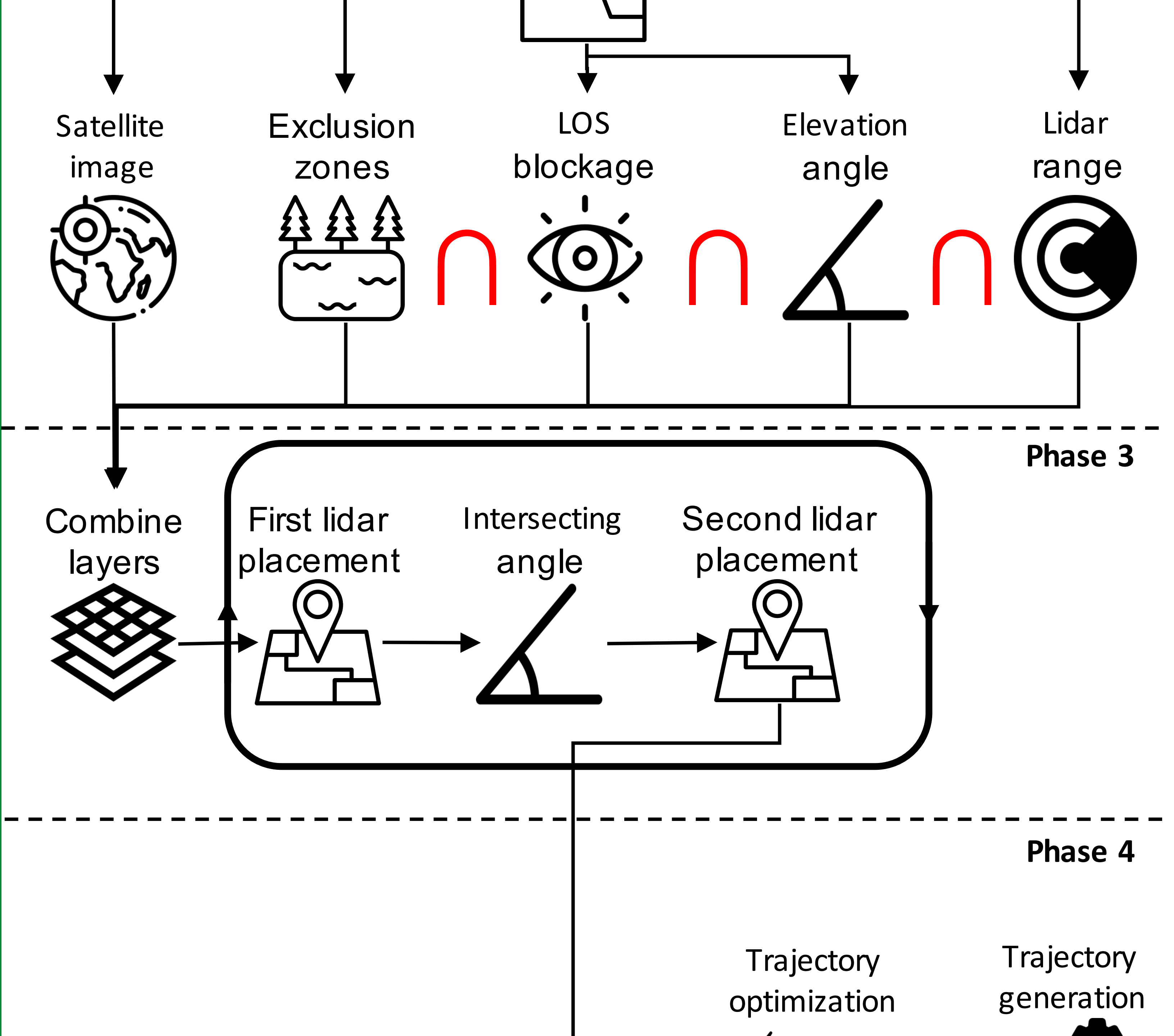


Workflow Phases

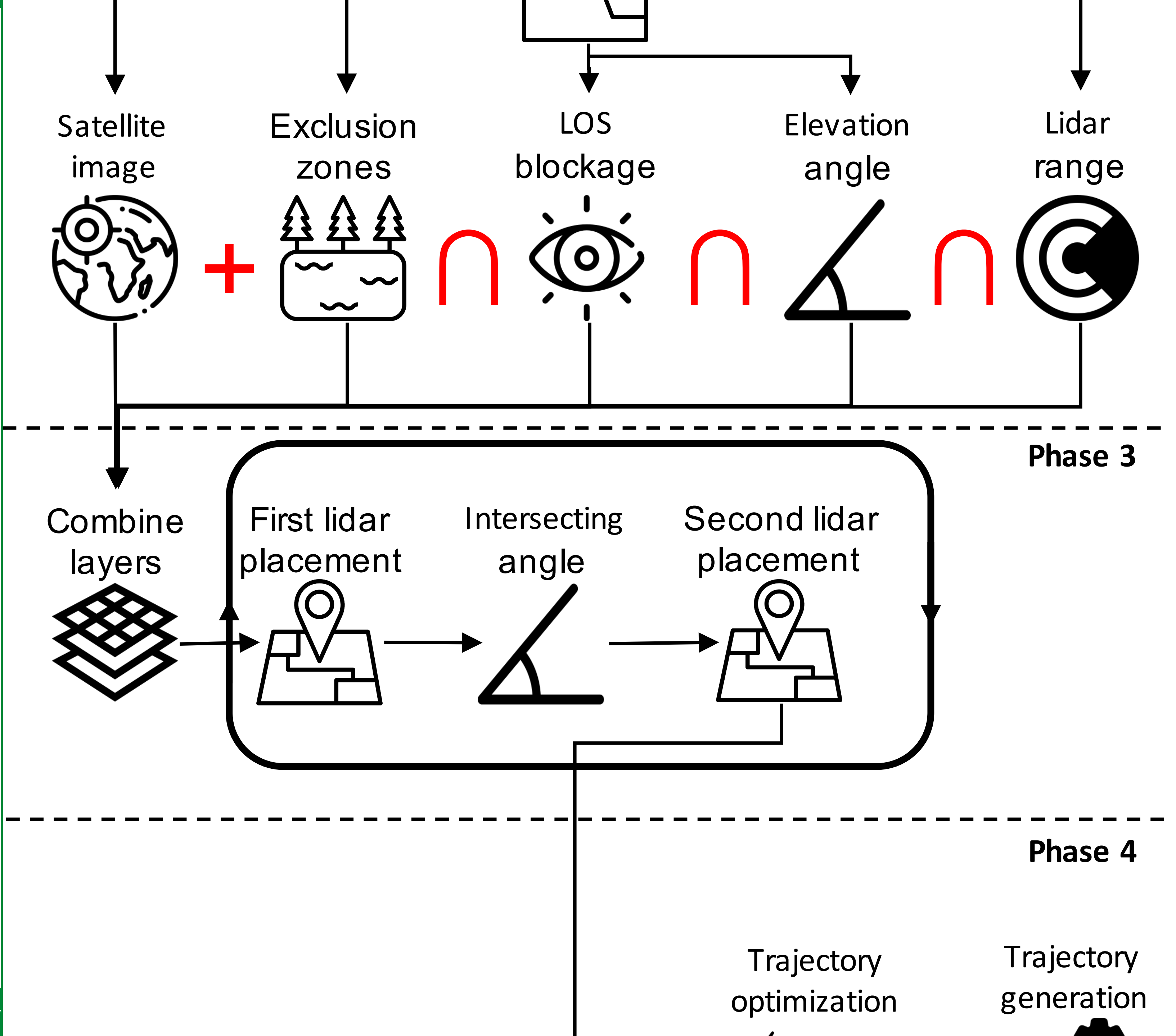



Phase 2
Canopy
Orography
Topography
Satellite image
Exclusion zones
LOS blockage
Elevation angle
Lidar range
Phase 3

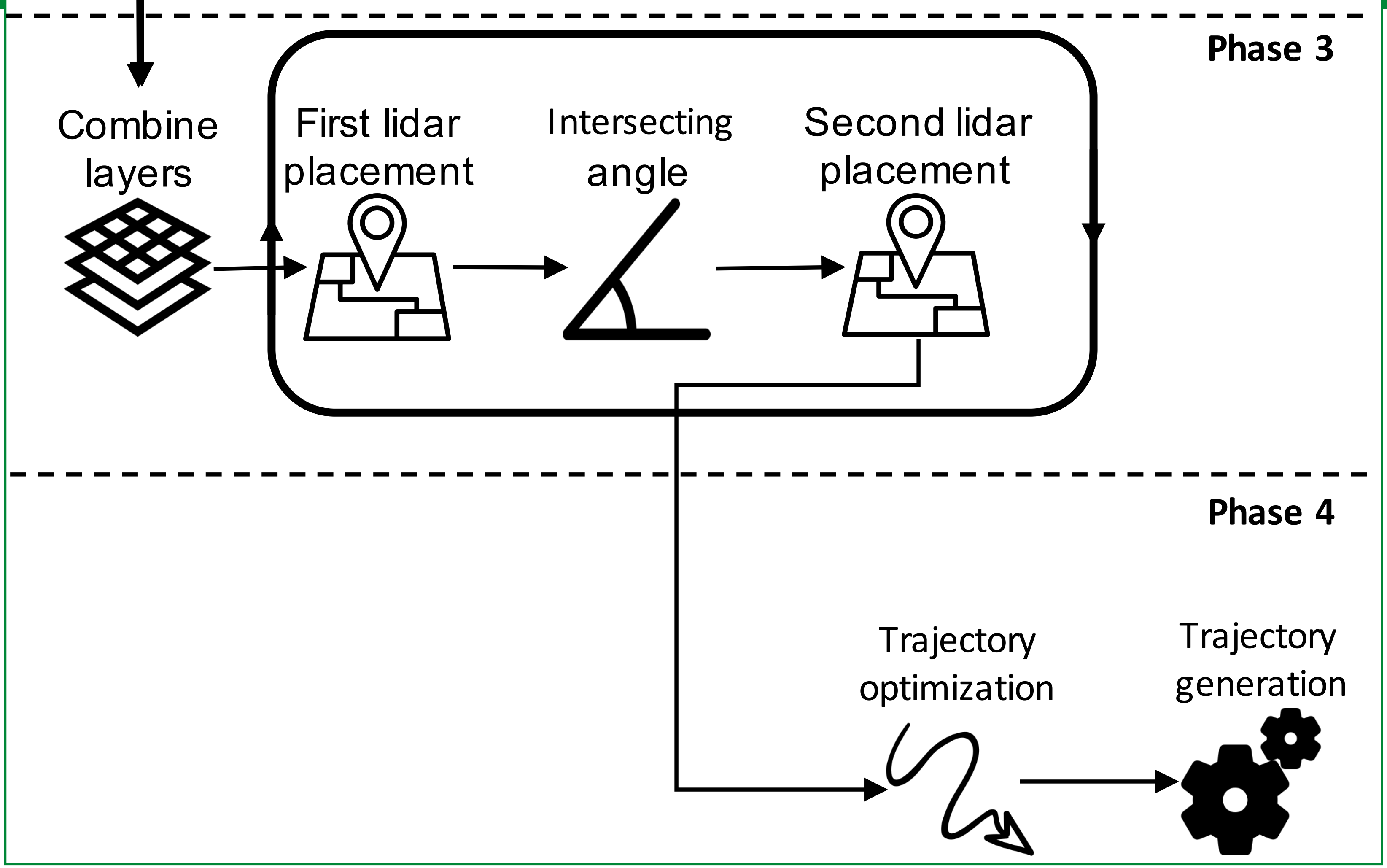

Satellite image
Exclusion zones
LOS blockage
Elevation angle
Lidar range
Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Phase 4
Trajectory optimization
Trajectory generation

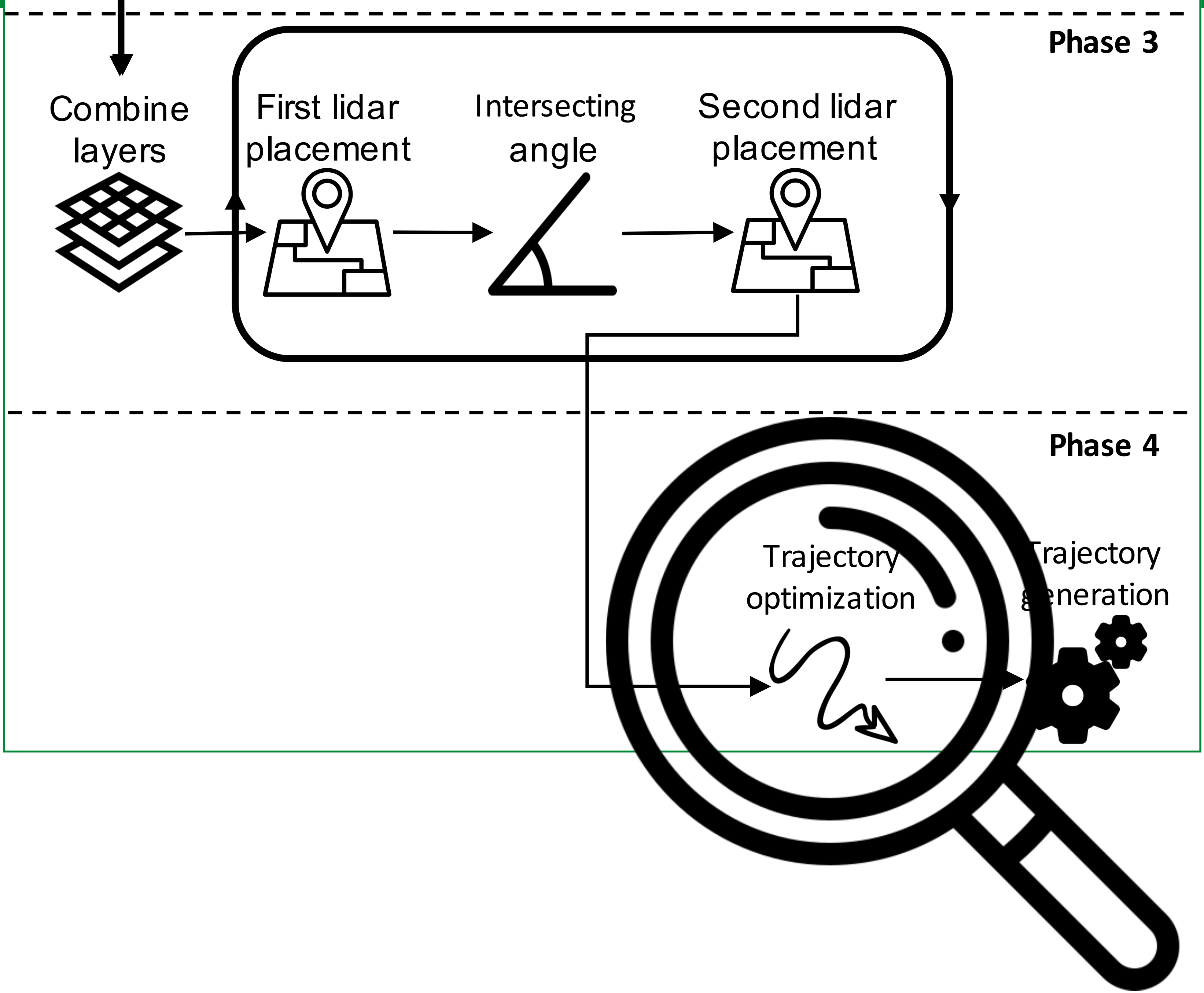

Satellite
image
Exclusion
zones
LOS
blockage
Elevation
angle
Lidar
range
Phase 3
Combine
layers
First lidar
placement
Intersecting
angle
Second lidar
placement
Phase 4
Trajectory
optimization
Trajectory
generation

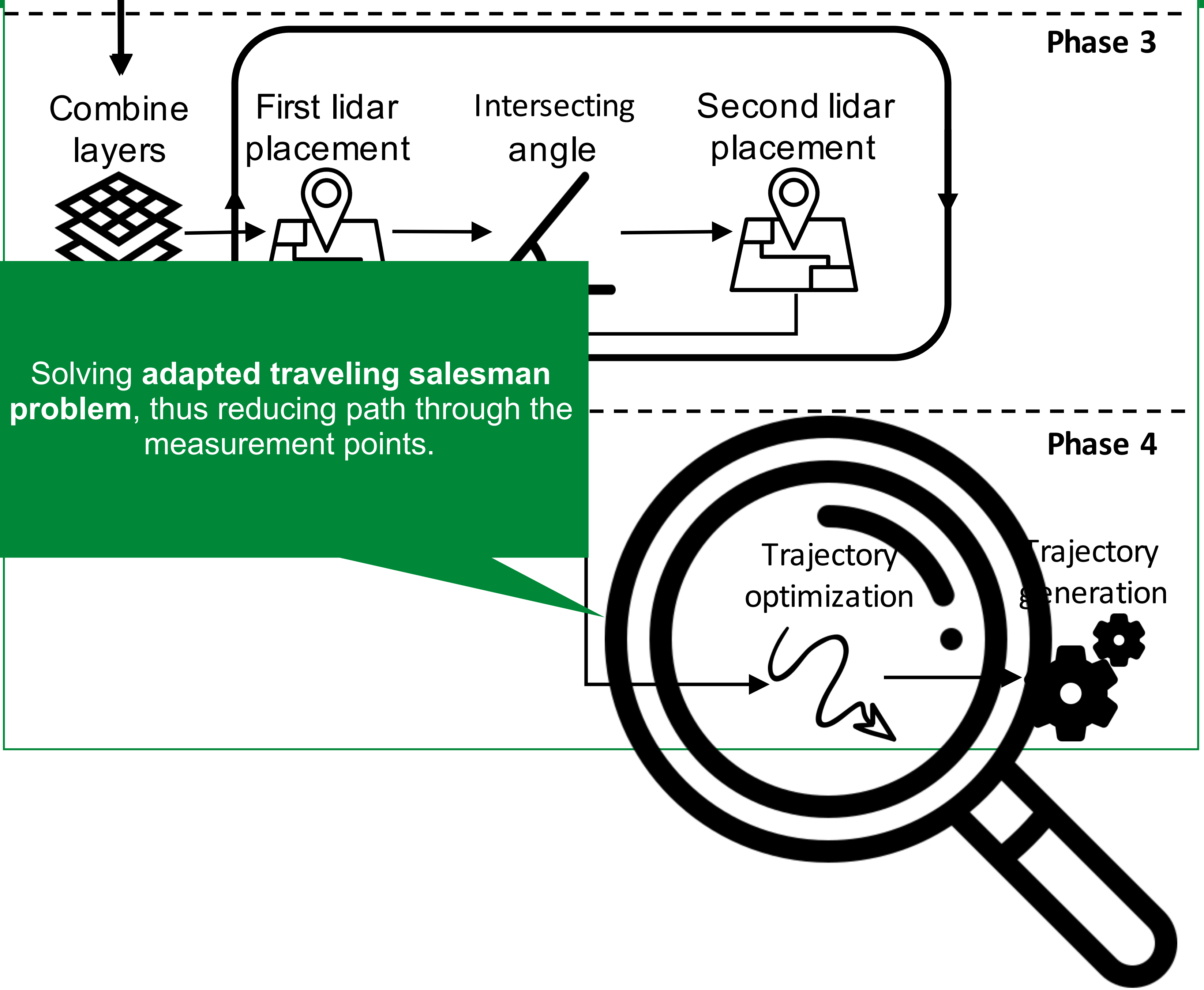
DTU



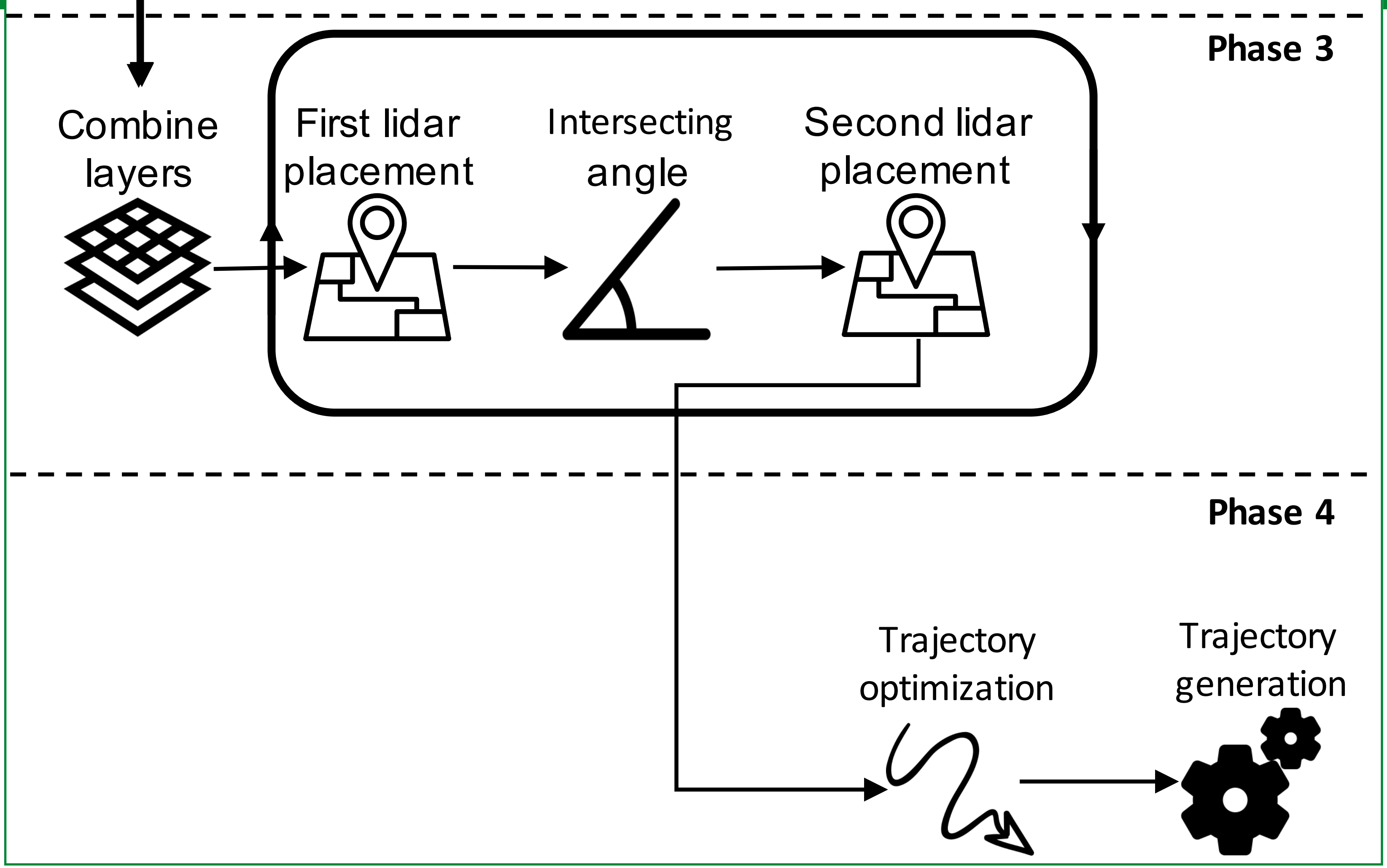
Satellite image
Exclusion zones
LOS blockage
Elevation angle
Lidar range
Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Phase 4
Trajectory optimization
Trajectory generation

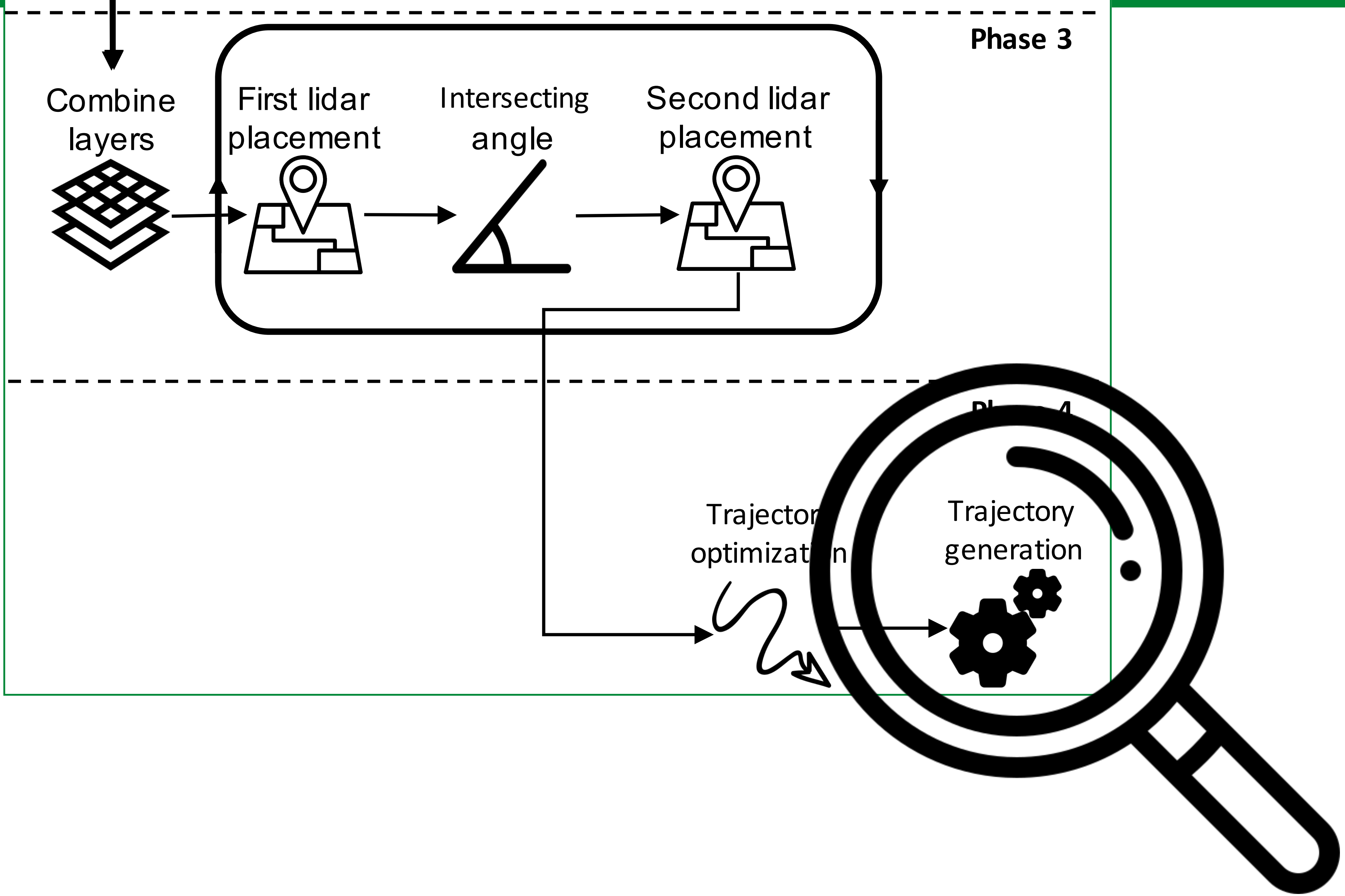

Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Phase 4
Trajectory optimization
Trajectory generation

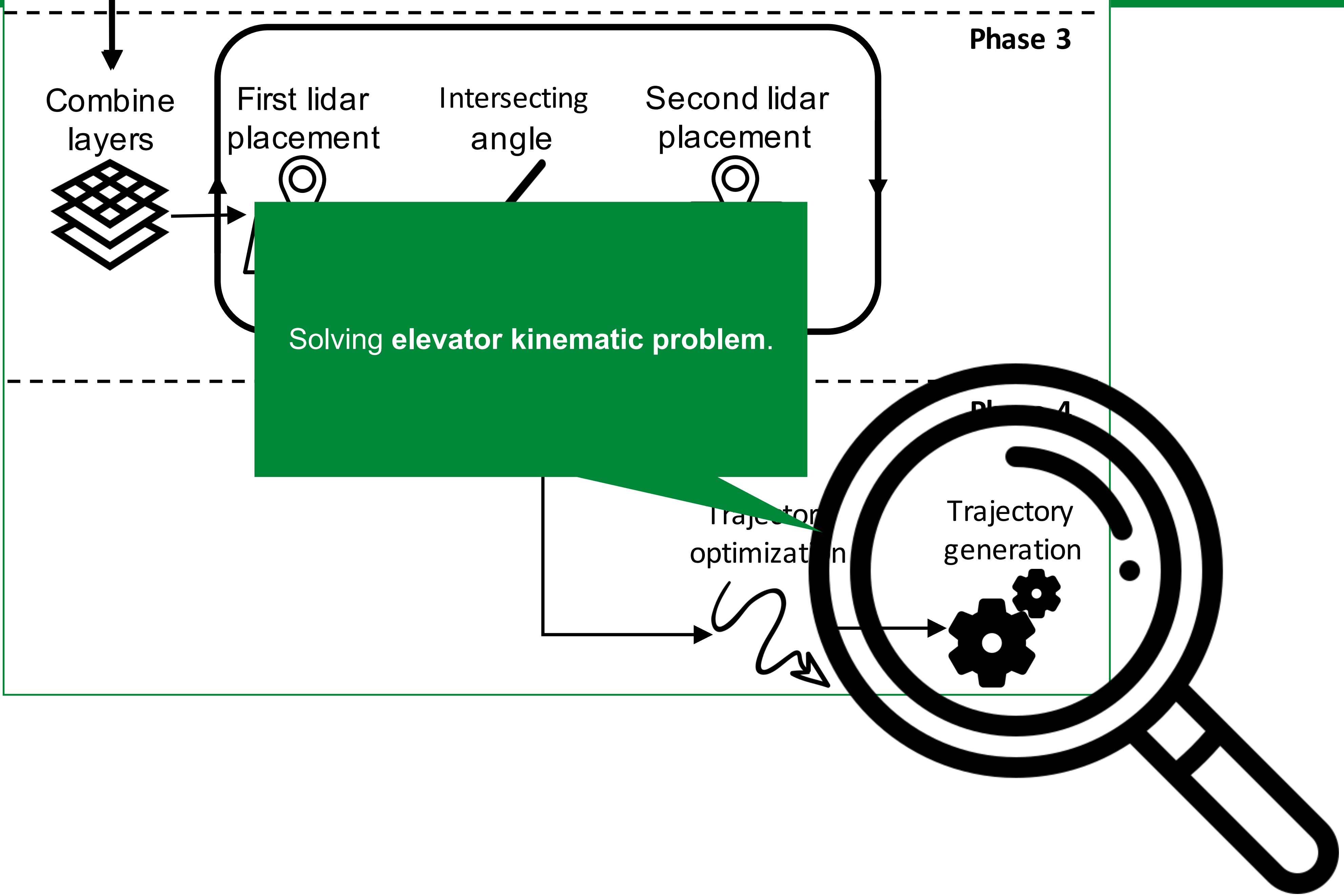

Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Phase 4
Trajectory optimization
Trajectory generation



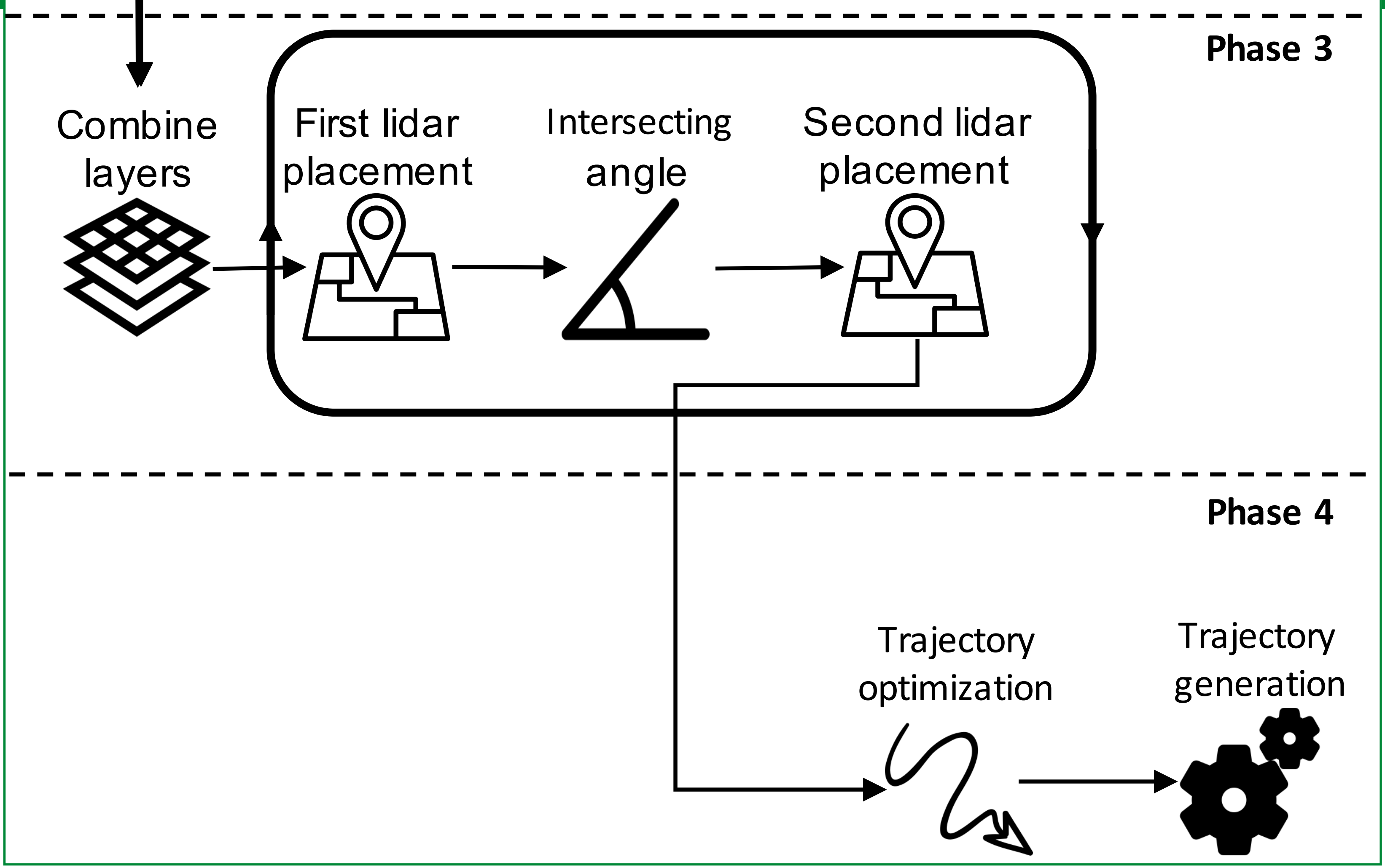
Solving **adapted traveling salesman problem**, thus reducing path through the measurement points.


Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Phase 4
Trajectory optimization
Trajectory generation

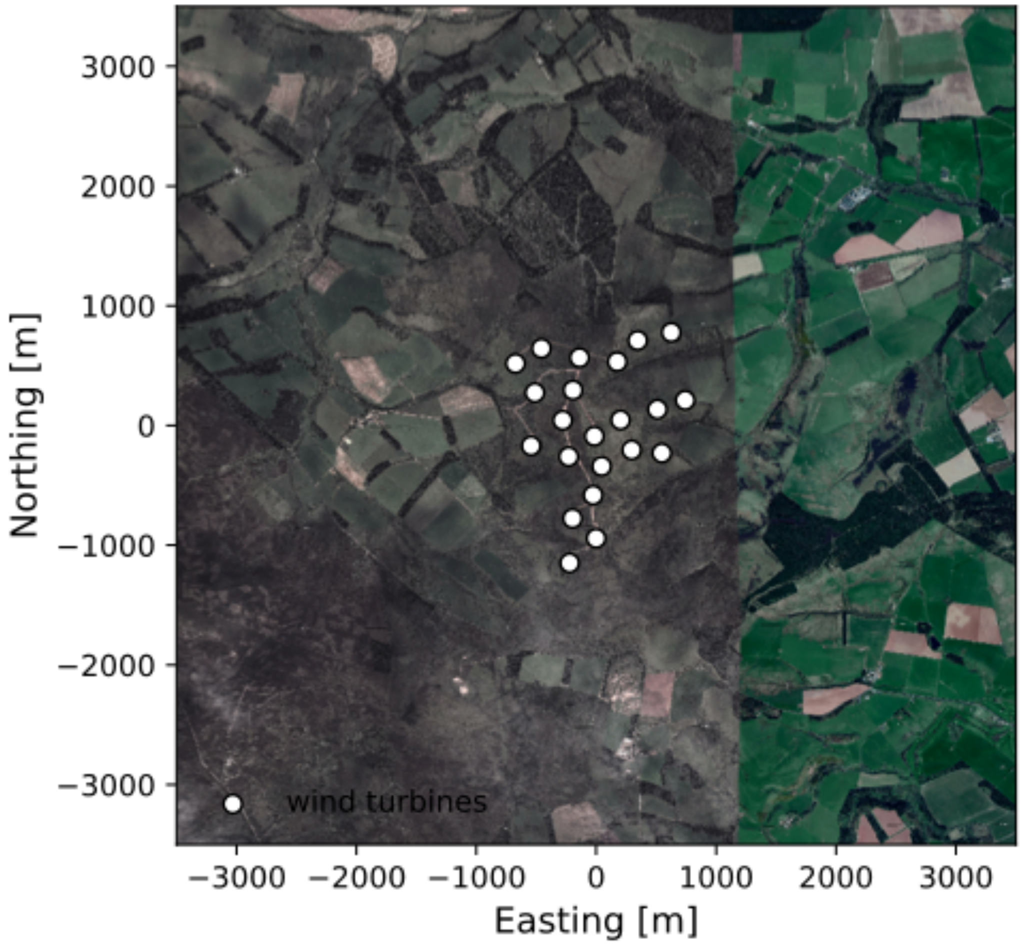

Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Trajectory optimization
Trajectory generation



Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Solving **elevator kinematic problem**.
Trajectory optimization
Trajectory generation


Phase 3
Combine layers
First lidar placement
Intersecting angle
Second lidar placement
Phase 4
Trajectory optimization
Trajectory generation

Example 1: Scottish site [10]

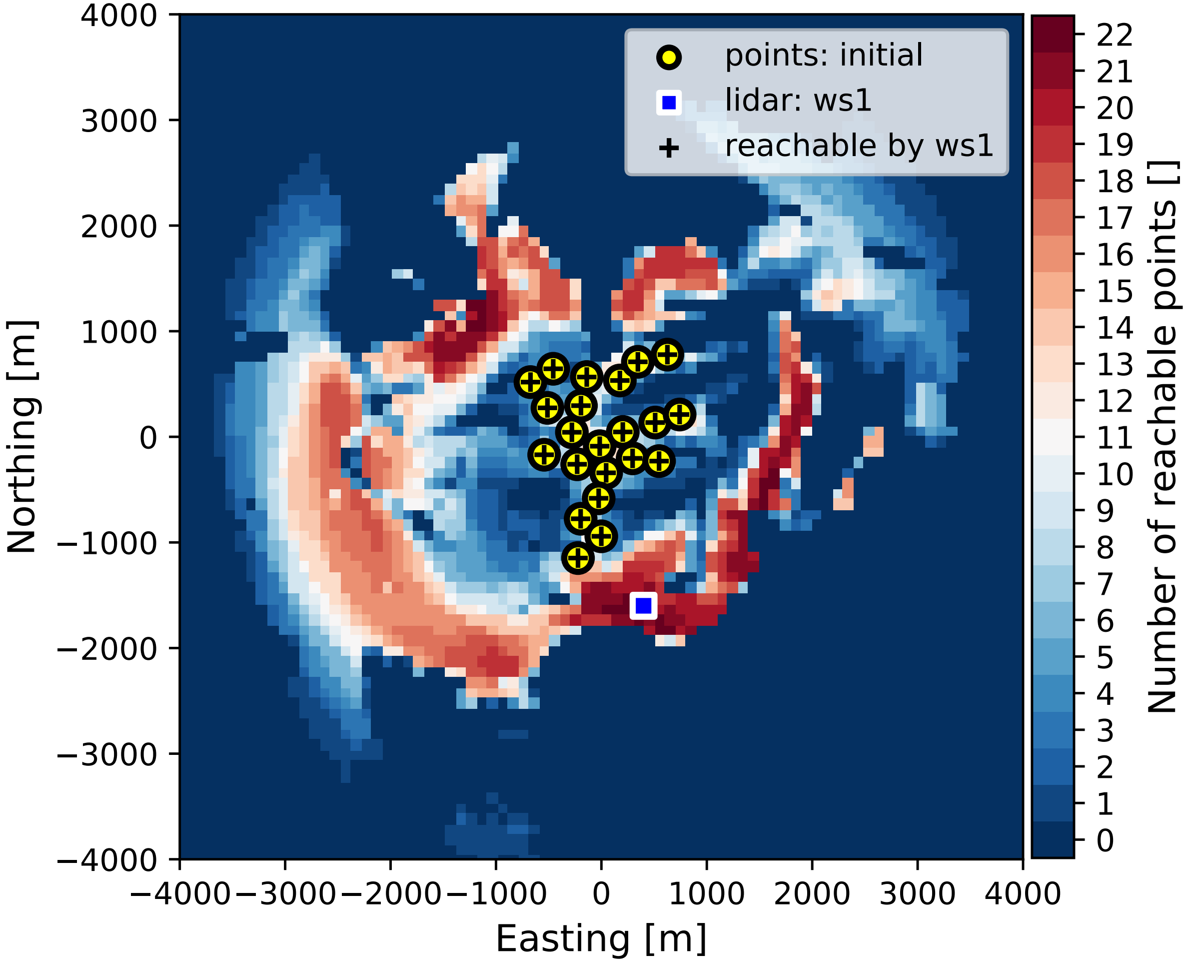


Info:

- 22 wind turbines with 47-m hub-heights
- Hilly terrain
- Aim to measure at each turbine position

[10] https://doi.org/10.11583/DTU.8343989.v3

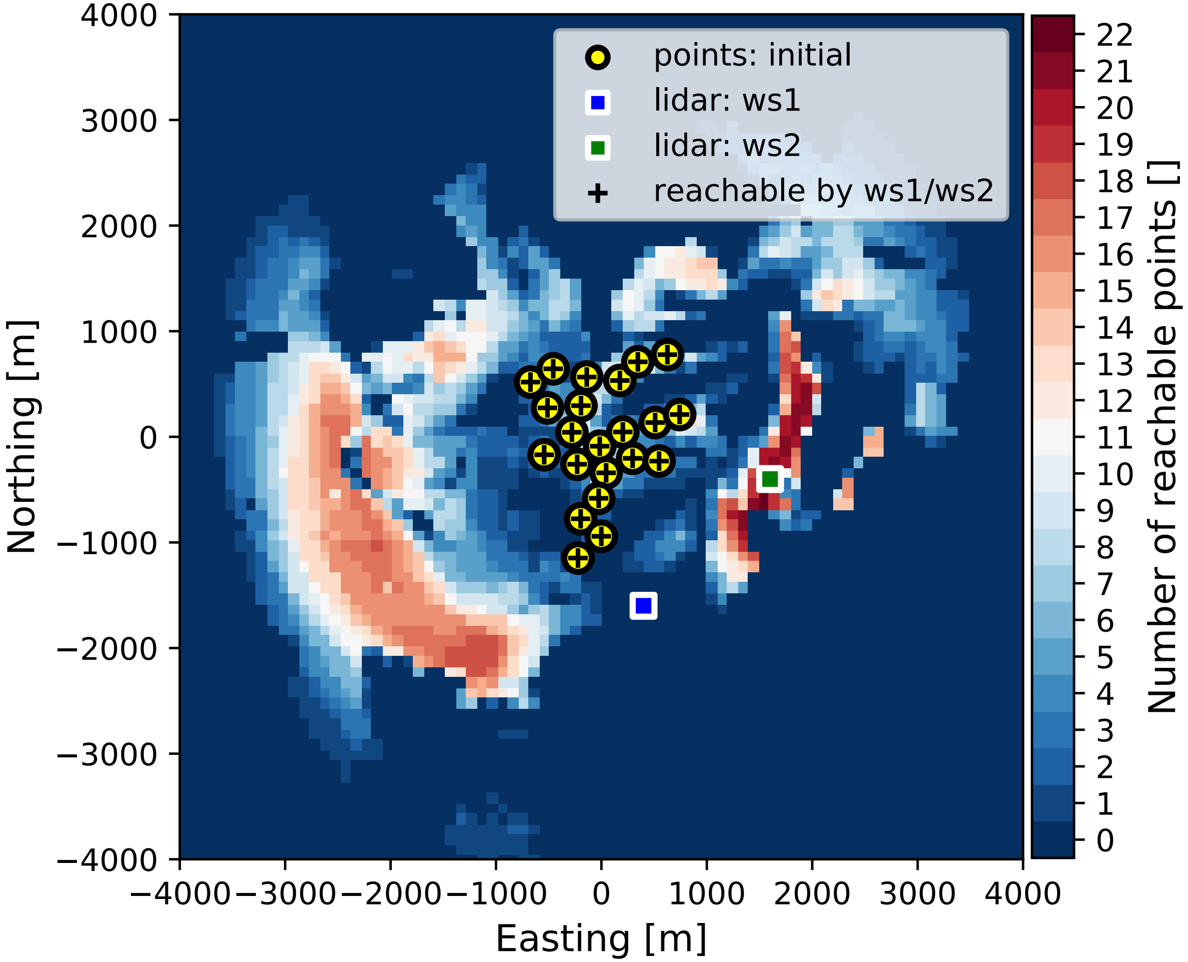
Example 1: Lidar placement GIS maps



Parameter	Value
Average range	3000 m
Max elevation angle	5°
Min intersecting angle	30°

Maps export to GeoTIFF / KML

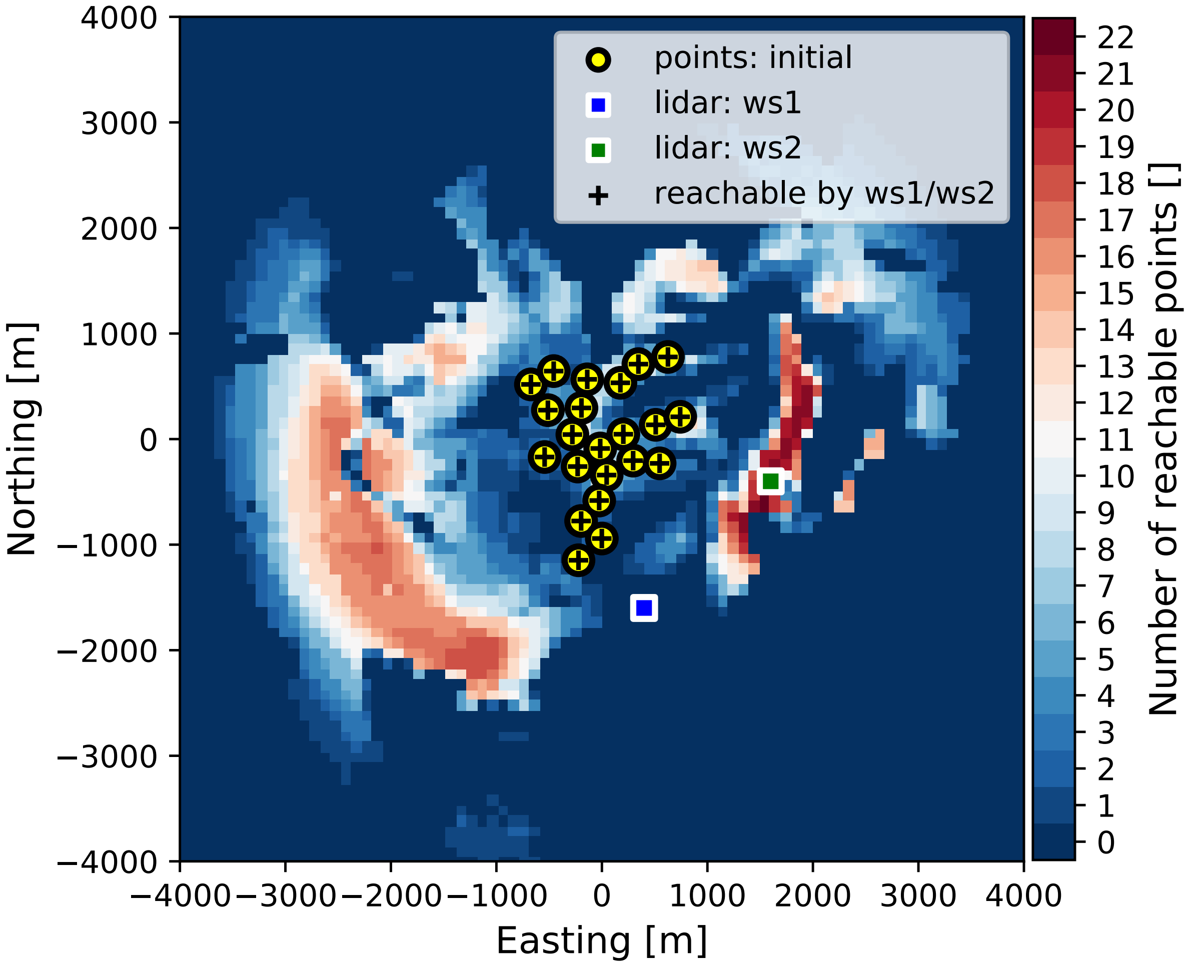
Example 1: Lidar placement GIS maps



Parameter	Value
Average range	3000 m
Max elevation angle	5°
Min intersecting angle	30°

Maps export to GeoTIFF / KML

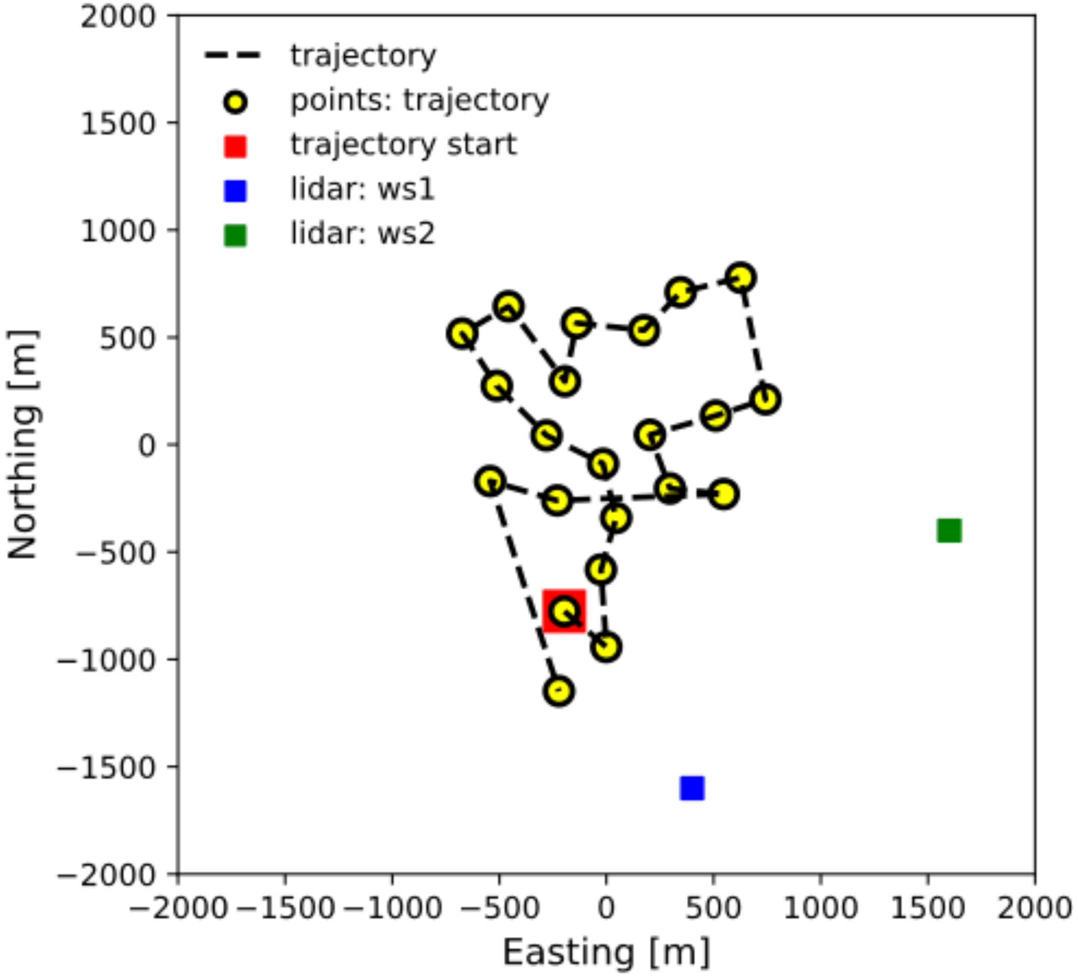
Example 1: Lidar placement GIS maps



Parameter	Value
Average range	3000 m
Max elevation angle	5°
Min intersecting angle	30°

Maps export to GeoTIFF / KML

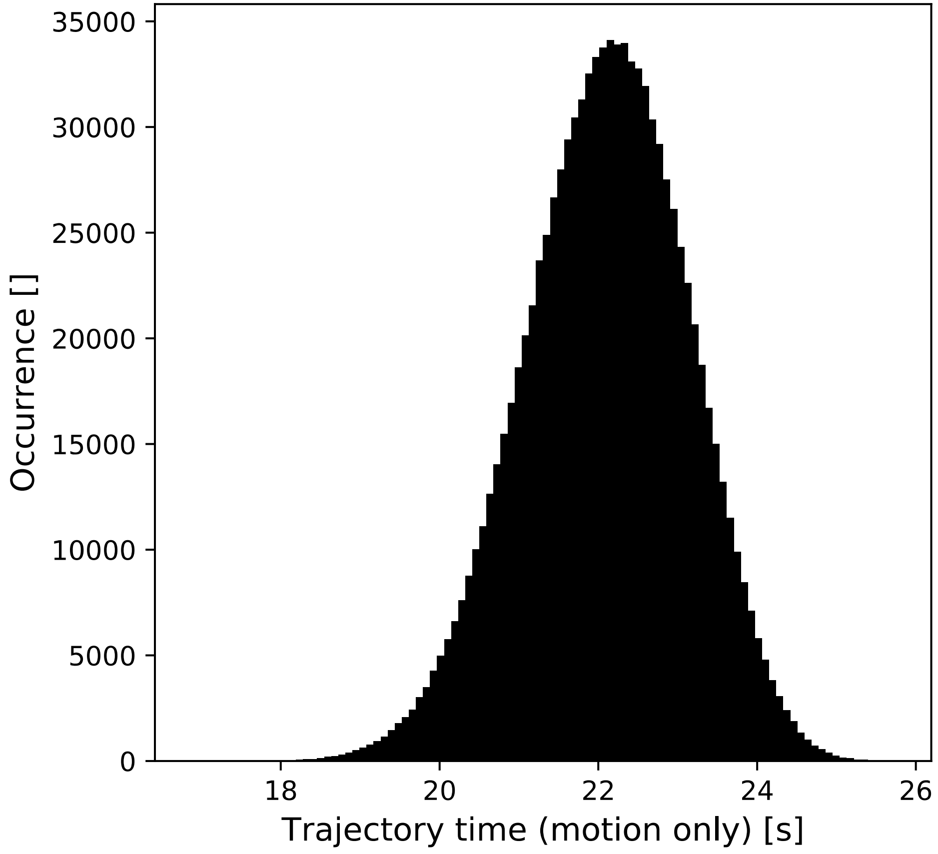
Example 1: Trajectory optimization and generation



Parameter	Value
Max speed	50˚/s
Max acceleration	100˚/s^2
Measurement time	22 s
Motion time	14 s
Trajectory time	36 s

Results export in multiple files

Example 1: How well the trajectory is optimized?

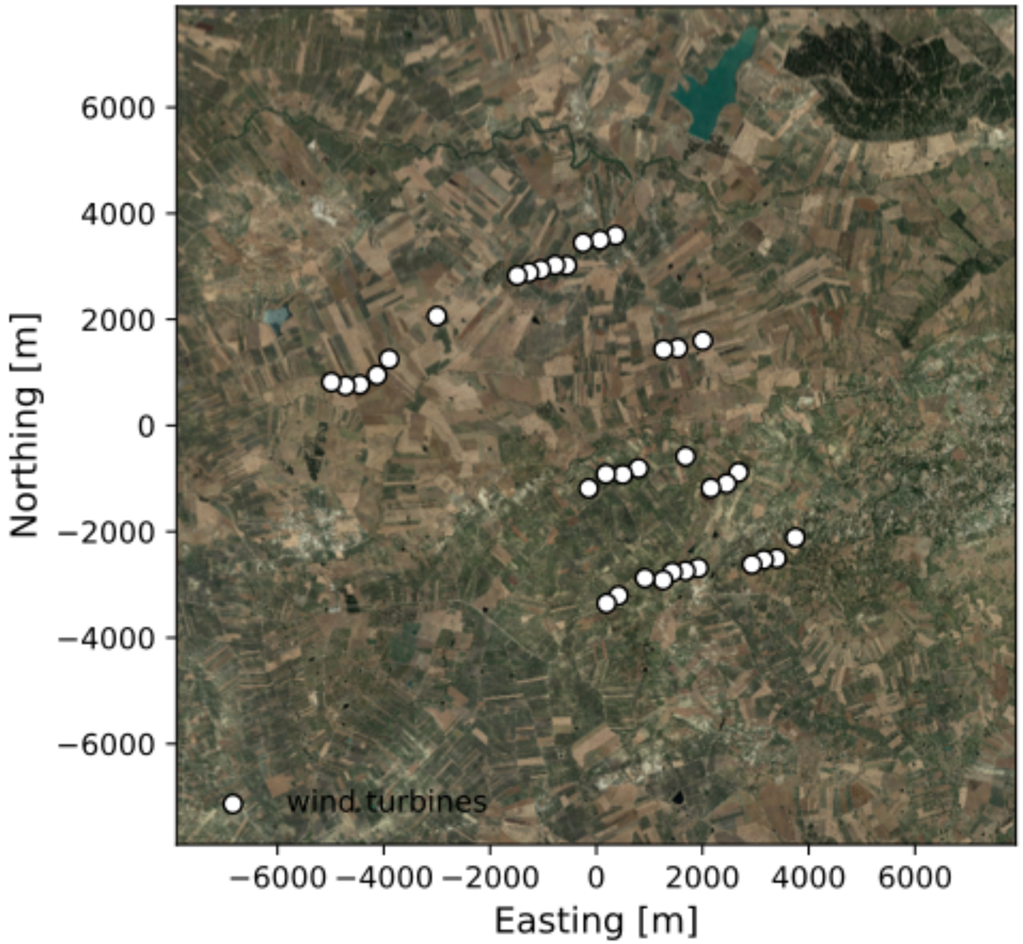


Parameter	Value
Mean motion time	22.09 s
Max motion time	25.76 s
Min motion time	17.15 s
Std motion time	1.03 s

A histogram of motion time for **10^6** randomly generated trajectory configurations for the Scottish site.

On average the optimized trajectory is 8 s shorter in duration!

Example 2: Italian site [11]

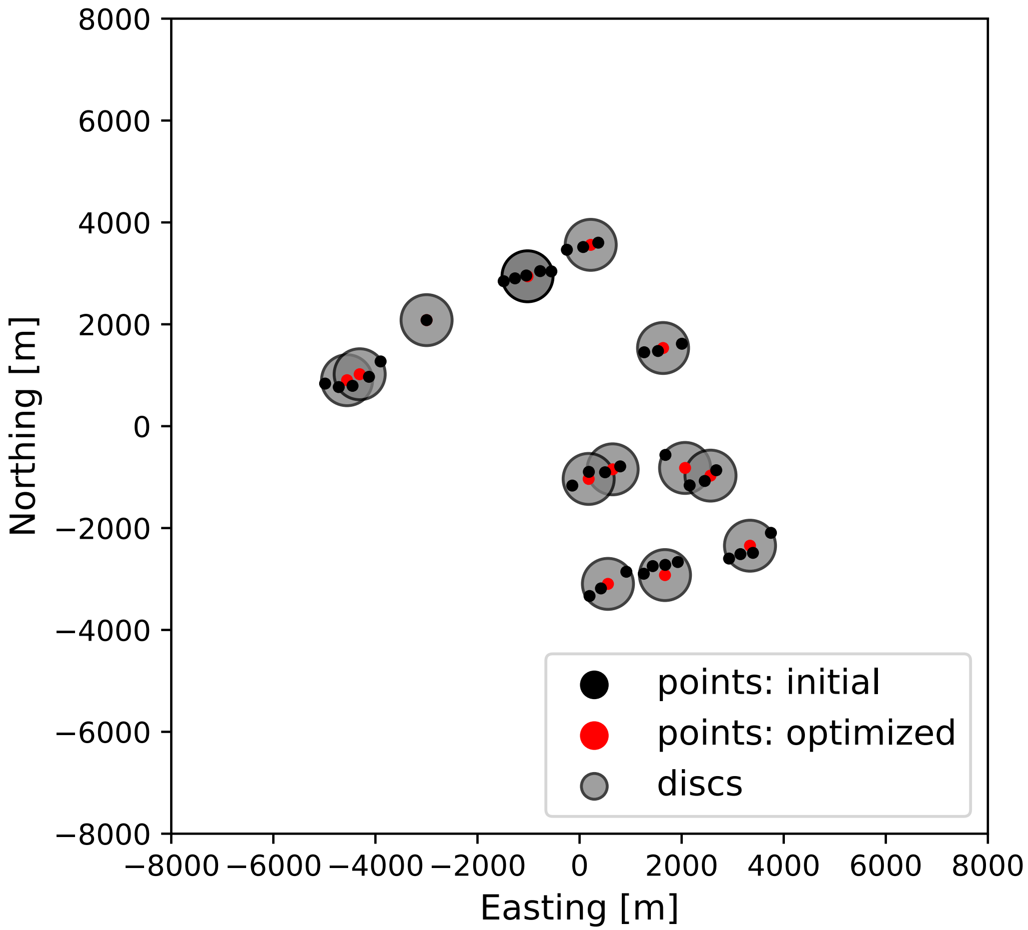


Info:

- 36 wind turbines with 78-m hub-heights
- Hilly terrain
- We will use measurement point optimization

[11] https://doi.org/10.11583/DTU.8343989.v3

Example 2: Measurement point optimization

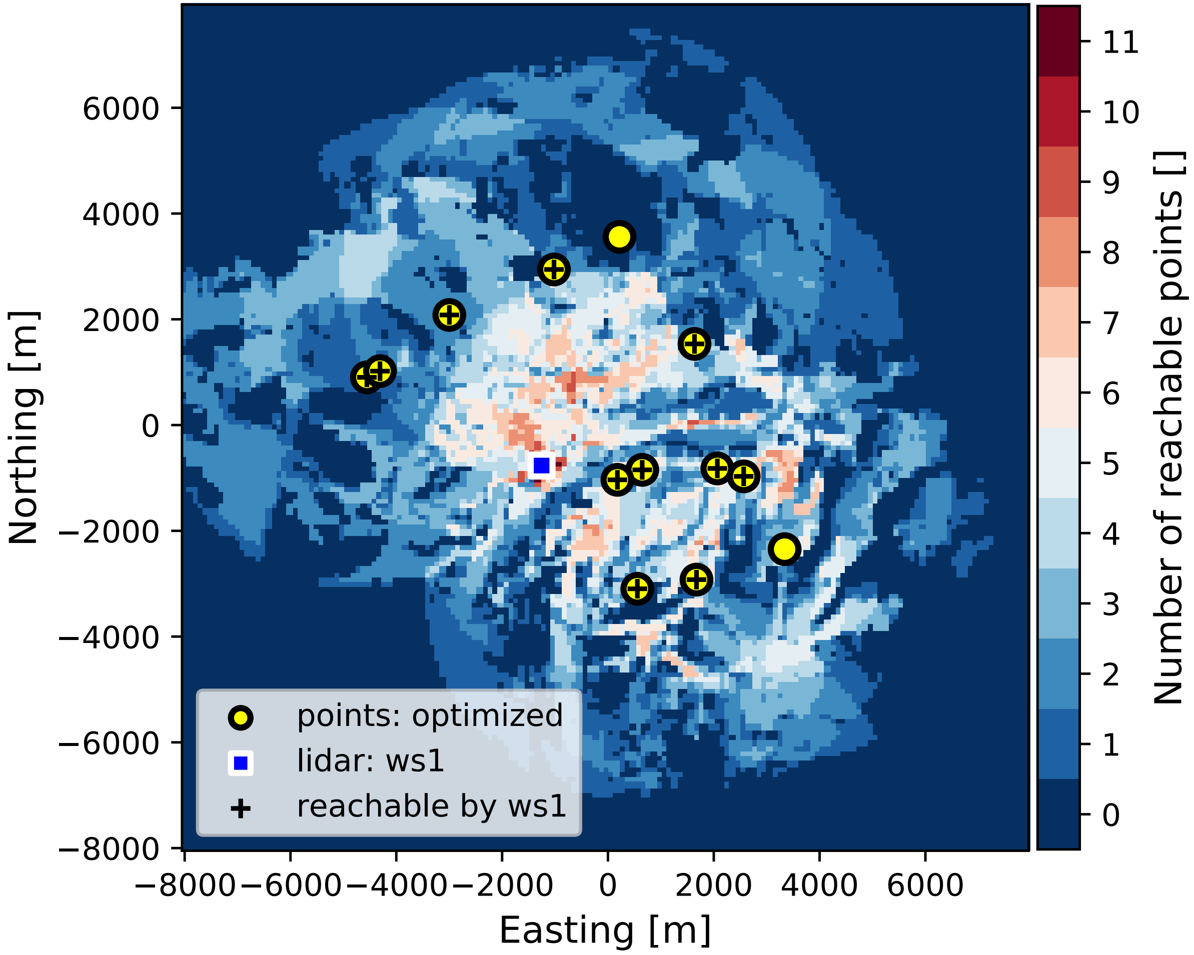


Parameter	Value
Representativeness radius [12]	500 m
No initial points	36
No optimized points	**13**

Reduction by 64%

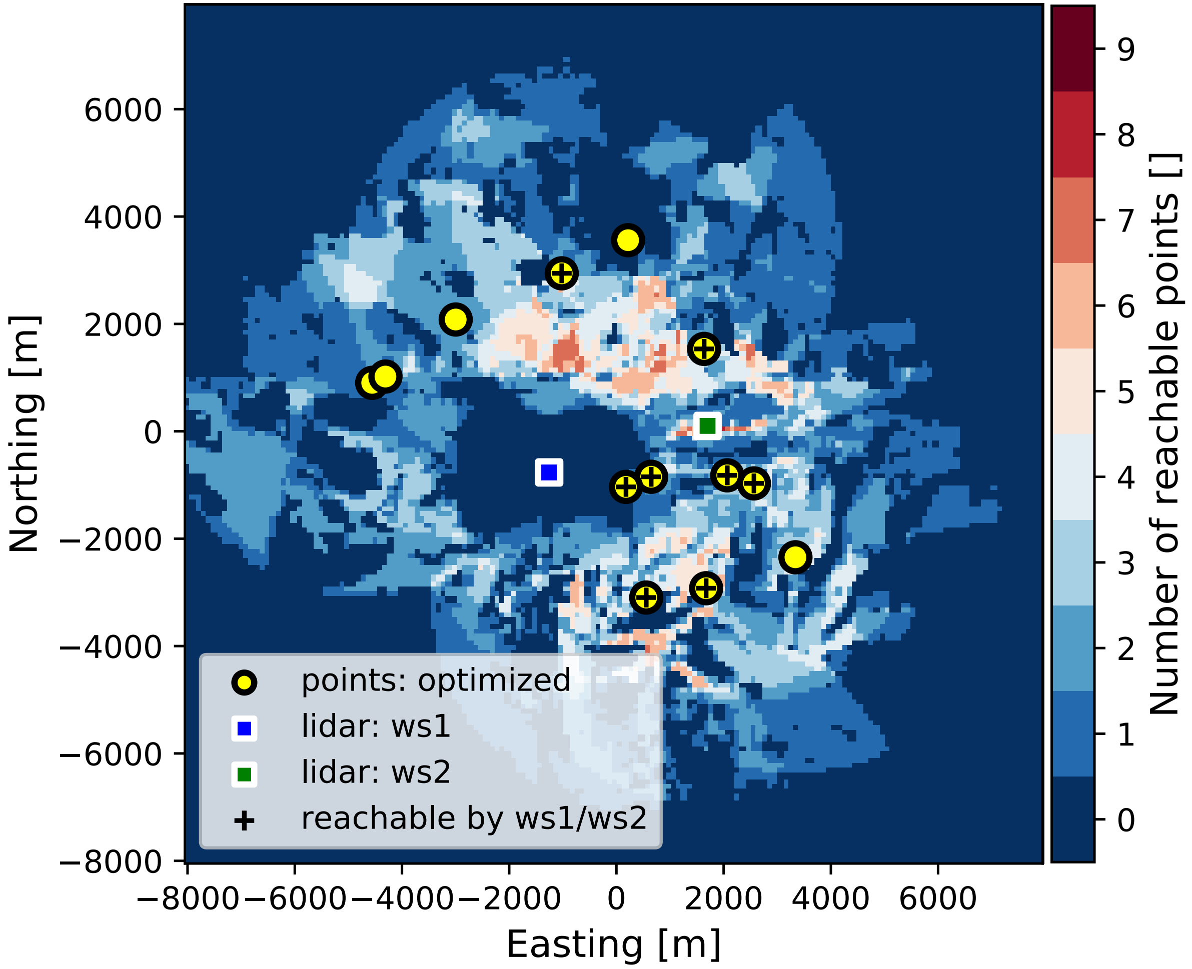
[12] MEASNET Procedure: Evaluation of Site-Specific Wind Conditions

Example 2: Lidar placement GIS maps



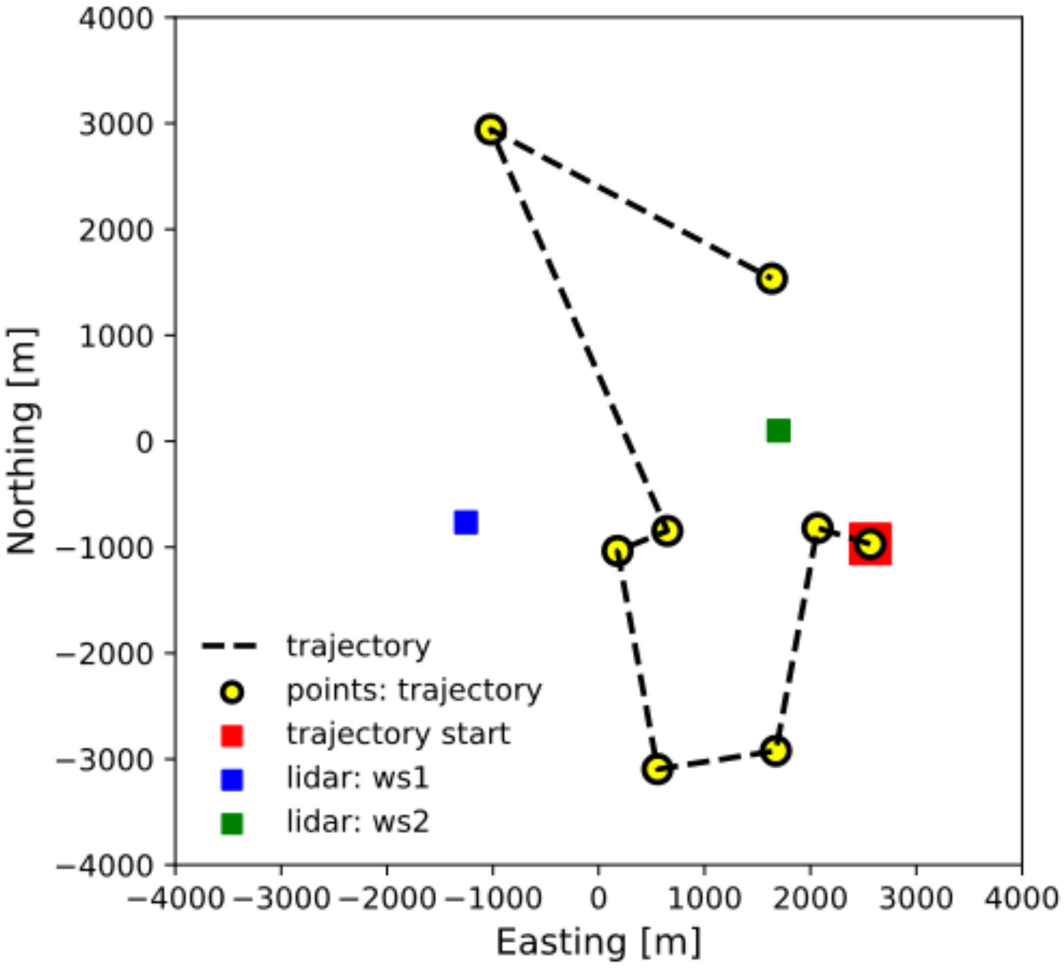
Parameter	Value
Average range	4000 m
Max elevation angle	5°
Min intersecting angle	30°

Example 2: Lidar placement GIS maps



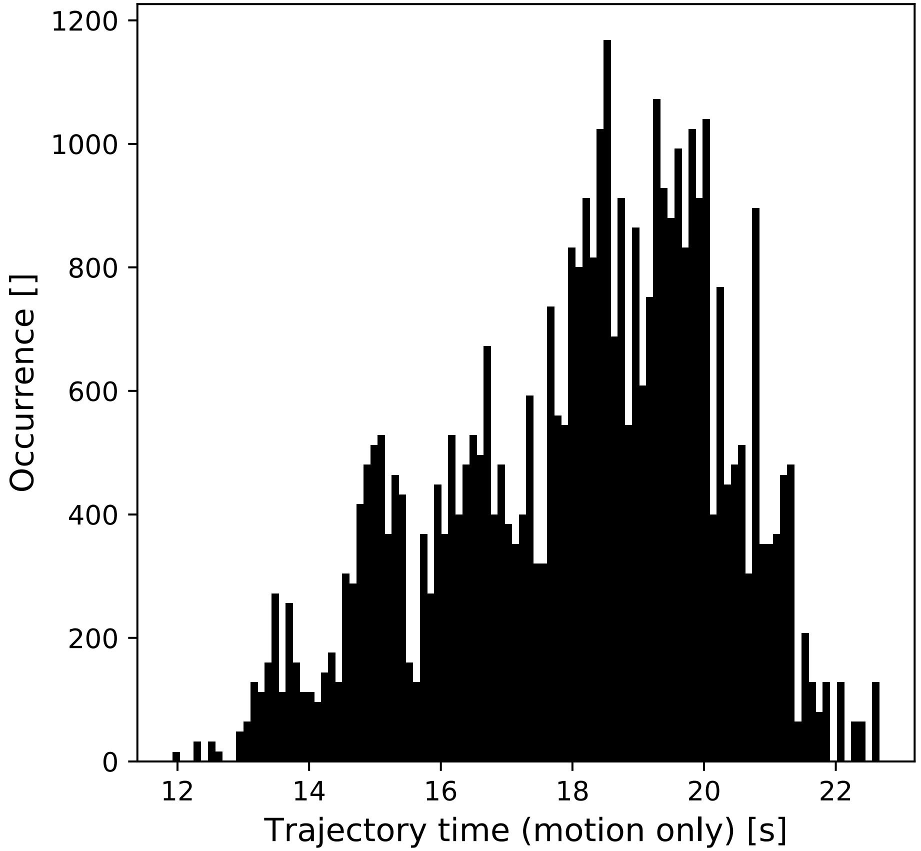
Parameter	Value
Average range	4000 m
Max elevation angle	5°
Min intersecting angle	30°

Example 2: Trajectory optimization and generation



Parameter	Value
Max speed	50˚/s
Max acceleration	100˚/s^2
Measurement time	8 s
Motion time	13 s
Trajectory time	21 s

Example 1: How well the trajectory is optimized?



Parameter	Value
Mean motion time	18.14 s
Max motion time	22.66 s
Min motion time	11.93 s
Std motion time	2.10 s

A histogram of motion time for 40320 unique trajectory configurations for the Italian site.

On average the optimized trajectory is 5 s shorter in duration!

Summary

- It takes **couple of minutes** to design and configure scanning lidar campaigns using *campaign-planning-tool* even for non-lidar experts, opposite to probably **days** if this is done manually by lidar experts

- The actual computational time to run *campaign-planning-tool* takes about **30 s**

- Optimizing measurement points can (depending on layout) reduce significantly number of measurement points => boost measurement rate

- Trajectory optimization matters since it can shed some seconds per each scan => boost measurement rate

How to get *campaign-planning-tool*

- Current public version 0.1.3 is provided via DTU Wind Energy's conda channel
- Check out Github repo for the installation instructions: https://github.com/niva83/campaign-planning-tool

Future work

- Youtube videos (screen recording + voice) with instructions how to use *campaign-planning-tool*
- If there is an interest webinar and/or workshop will be organize
- Develop range prediction module
- Develop data availability prediction module
- Develop eye safety check module

DTU contributions to OpenLidar initiative

- In collaboration with ForWind developed Remote Sensing Communication Protocol [13]
- Contributed to the OpenLidar architecture
- In collaboration with ZX Lidars developed proof-of-concept drone-based wind lidar [14]

[13] https://orbit.dtu.dk/ws/files/59175330/The_application_layer_protocol.pdf

[14] https://www.atmos-meas-tech-discuss.net/amt-2019-102/

OpenLidar

DTU contributions to OpenLidar initiative

- In collaboration with ForWind developed Remote Sensing Communication Protocol [13]
- Contributed to the OpenLidar architecture
- In collaboration with ZX Lidars developed proof-of-concept drone-based wind lidar [14]

[13] https://orbit.dtu.dk/ws/files/59175330/The_application_layer_protocol.pdf

[14] https://www.atmos-meas-tech-discuss.net/amt-2019-102/

In quest for …

– Low cost accurate measurements

– High frequency small probe volume

– High availability of data

– Simple sophisticated measurements

Slide source: https://zenodo.org/record/3249999

Promising solution

- Use of drones as platforms for wind lidars

- Drones would be used to:
  – to position the lidar in the vicinity of the measurement points
  – to steer the outgoing laser beam

Slide source: https://zenodo.org/record/3249999

Impact of such solution

Impact of such solution

- Relax a requirement on maximum range (a few meters would be enough)

Impact of such solution

- Relax a requirement on maximum range (a few meters would be enough)
- No need to have a variable focus

Impact of such solution

- Relax a requirement on maximum range (a few meters would be enough)
- No need to have a variable focus
- No need to have a scanning mechanism

Impact of such solution

- Relax a requirement on maximum range (a few meters would be enough)
- No need to have a variable focus
- No need to have a scanning mechanism
- No need to have an acousto-optic modulator (AOM)

Slide source: https://zenodo.org/record/3249999

Impact of such solution

- Relax a requirement on maximum range (a few meters would be enough)
- No need to have a variable focus
- No need to have a scanning mechanism
- No need to have an acousto-optic modulator (AOM)
- A significant reduction in the lidar complexity (fewer and cheaper components), size, weight and power consumption, and thus potentially in the overall costs.

Slide source: https://zenodo.org/record/3249999

Impact of such solution

- Relax a requirement on maximum range (a few meters would be enough)
- No need to have a variable focus
- No need to have a scanning mechanism
- No need to have an acousto-optic modulator (AOM)
- A significant reduction in the lidar complexity (fewer and cheaper components), size, weight and power consumption, and thus potentially in the overall costs.
- The requirements for the drone-mounted lidar can be met by a low-power small-optics CW lidar with a manual focus adjustment.

Slide source: https://zenodo.org/record/3249999

Impact of such solution - continued

Slide source: https://zenodo.org/record/3249999

Impact of such solution - continued

- High frequency measurements (50 Hz)

Impact of such solution - continued

- High frequency measurements (50 Hz)
- Short focus distance = small probe length (~10 cm)

Slide source: https://zenodo.org/record/3249999

Impact of such solution - continued

- High frequency measurements (50 Hz)
- Short focus distance = small probe length (~10 cm)
- Short-range measurements would not be hindered by fog or clouds
  => improved data availability

Impact of such solution - continued

- High frequency measurements (50 Hz)
- Short focus distance = small probe length (~10 cm)
- Short-range measurements would not be hindered by fog or clouds
  => improved data availability
- Measurement can be made in difficult locations

Slide source: https://zenodo.org/record/3249999

Impact of such solution - continued

- High frequency measurements (50 Hz)
- Short focus distance = small probe length (~10 cm)
- Short-range measurements would not be hindered by fog or clouds
  => improved data availability
- Measurement can be made in difficult locations
- We don’t need to develop drones, drones are everywhere and developed by others

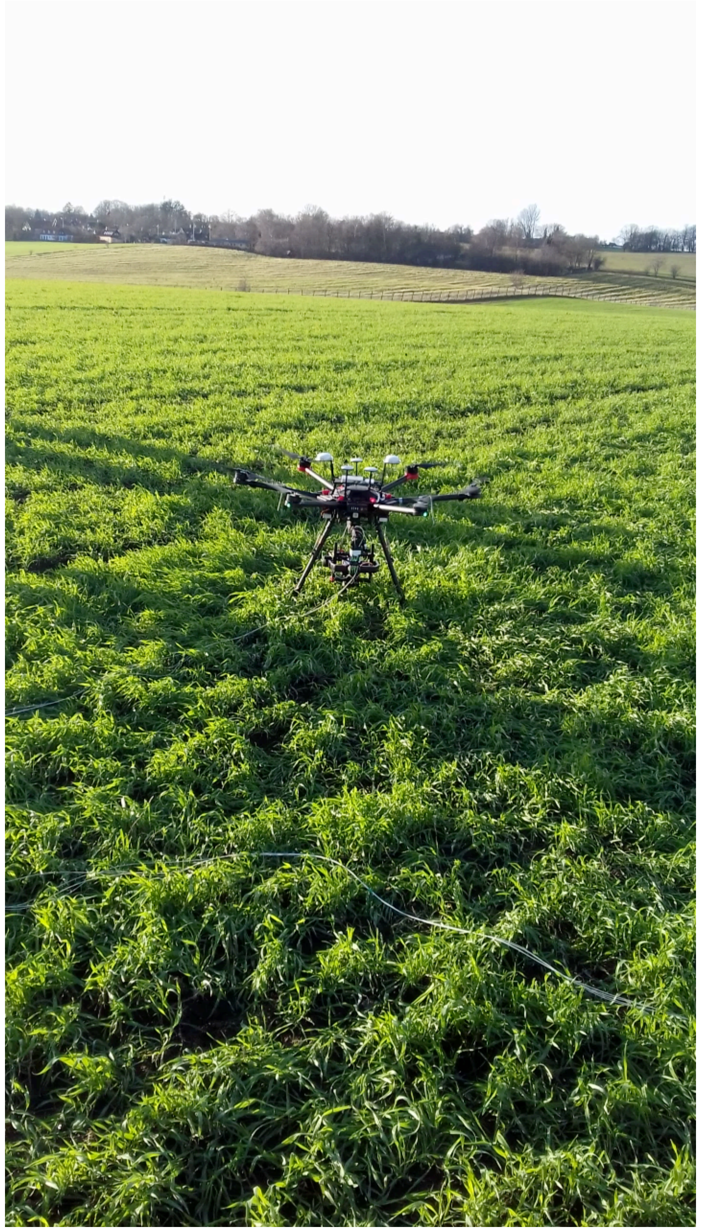
Slide source: https://zenodo.org/record/3249999

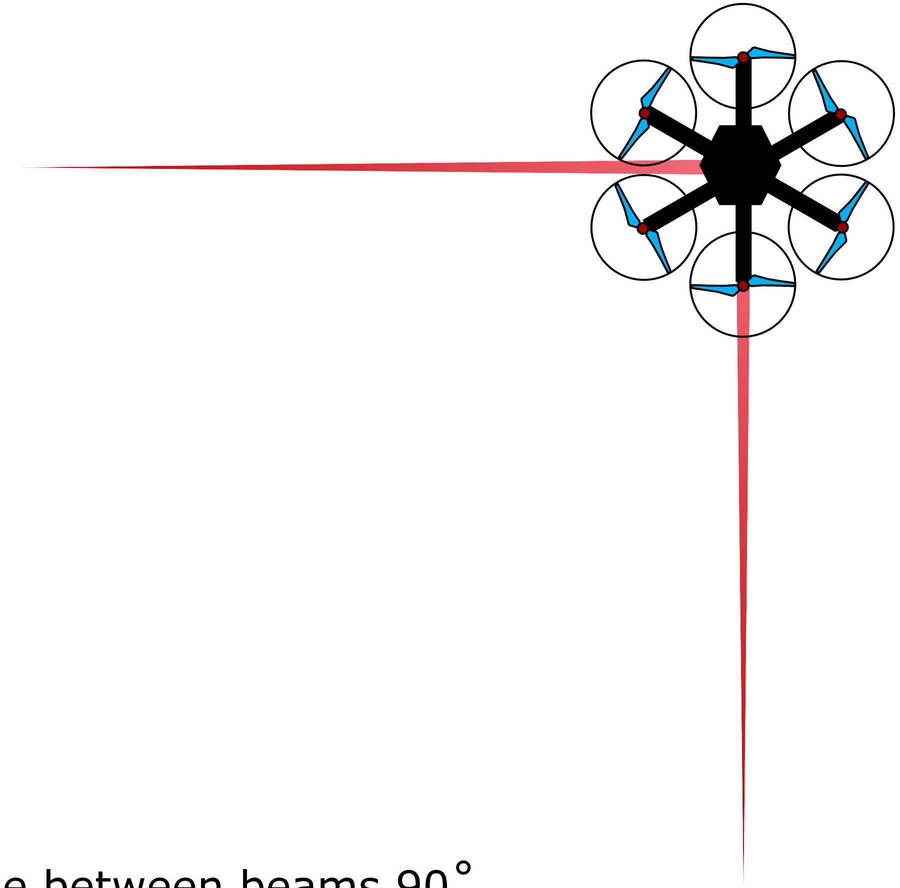
Dual-telescope proof-of-concept, Denmark

See picture gallery:
https://work.courtney.dk/#collection/364601

3 – 5 /12/2019 – proof-of-concept with a dual-single telescope system

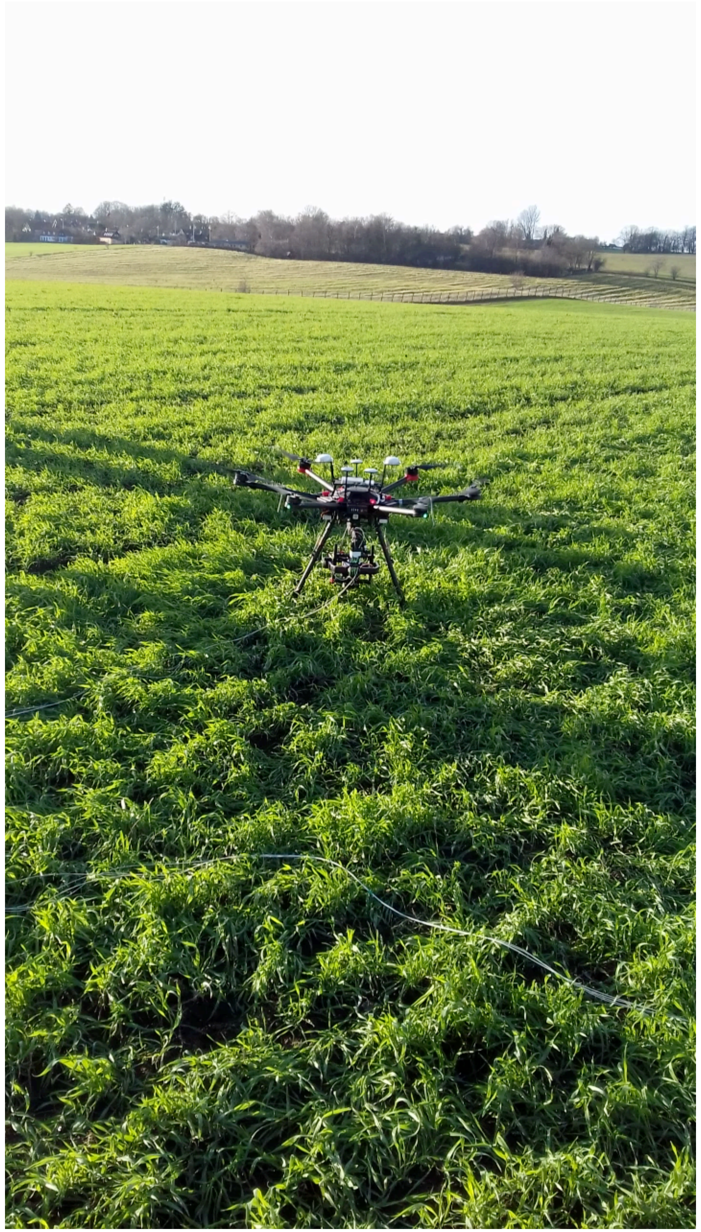
Slide source: https://zenodo.org/record/3249999

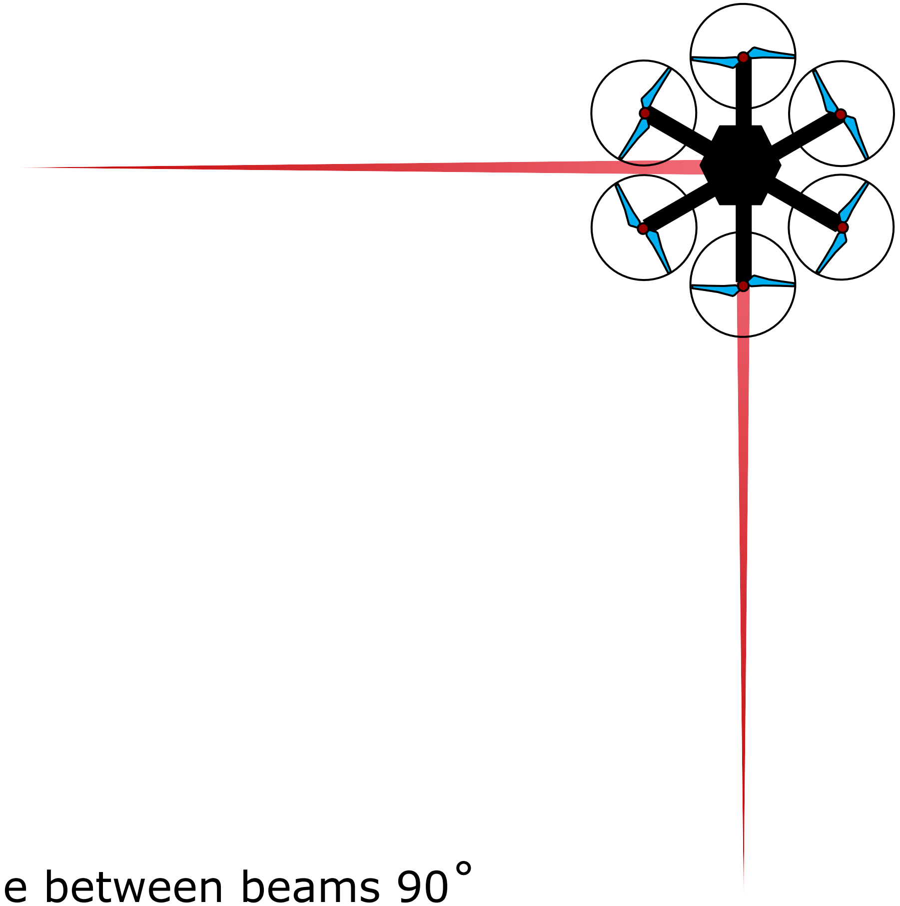




Angle between beams 90°
Effective probe length 25 cm
Beams focused @ 5 m
0.3 W per telescope
100% duty-cycle on both channels

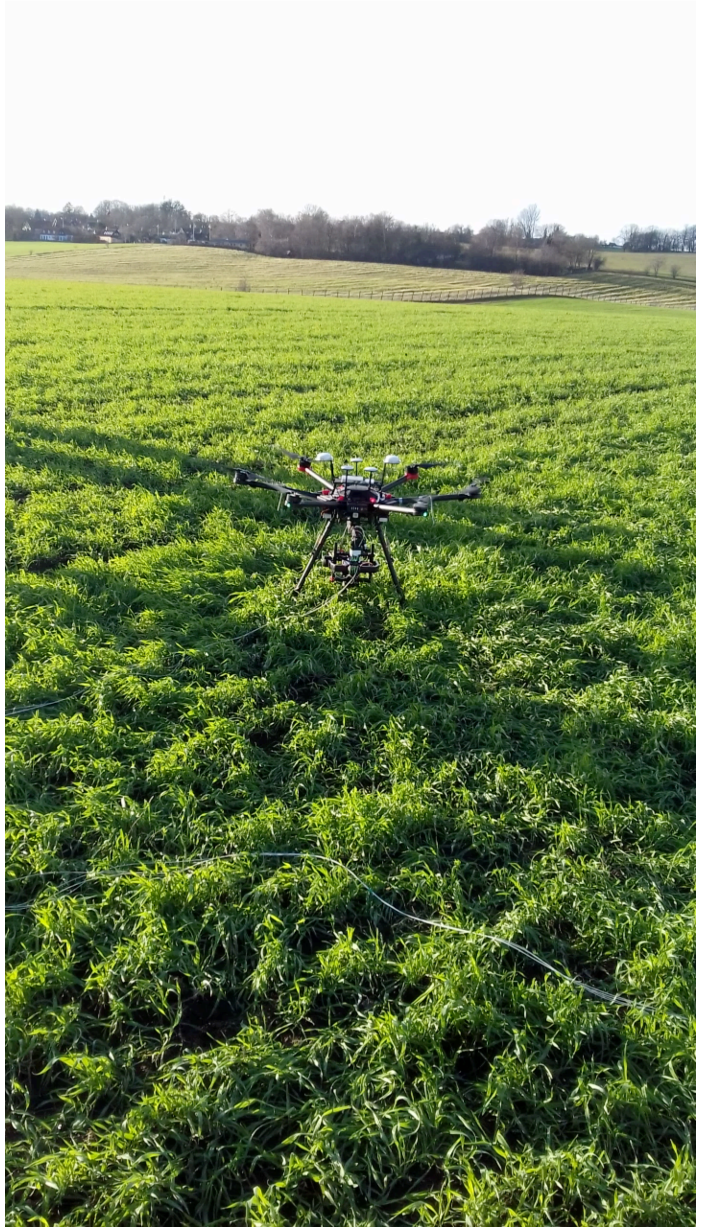
Slide source: https://zenodo.org/record/3249999

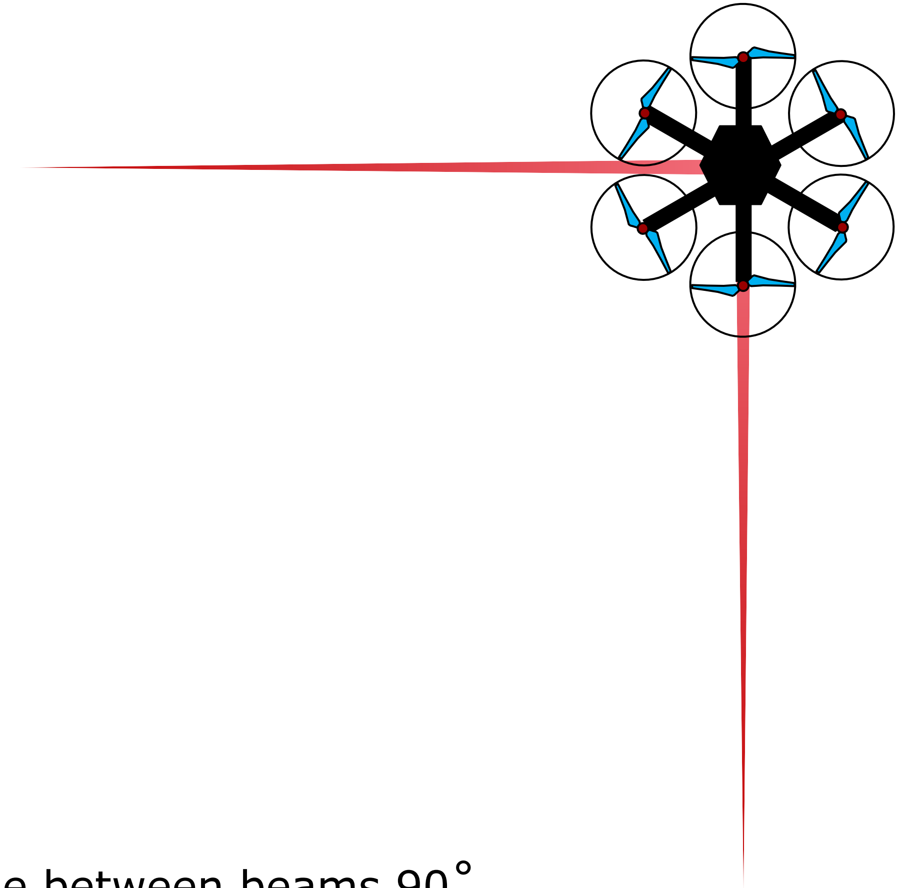




Angle between beams 90°
Effective probe length 25 cm
Beams focused @ 5 m
0.3 W per telescope
100% duty-cycle on both channels

Slide source: https://zenodo.org/record/3249999





Angle between beams 90°
Effective probe length 25 cm
Beams focused @ 5 m
0.3 W per telescope
100% duty-cycle on both channels

Dual-telescope setup

Measurements next to sonic at 70 m

V52 met mast at Risø campus

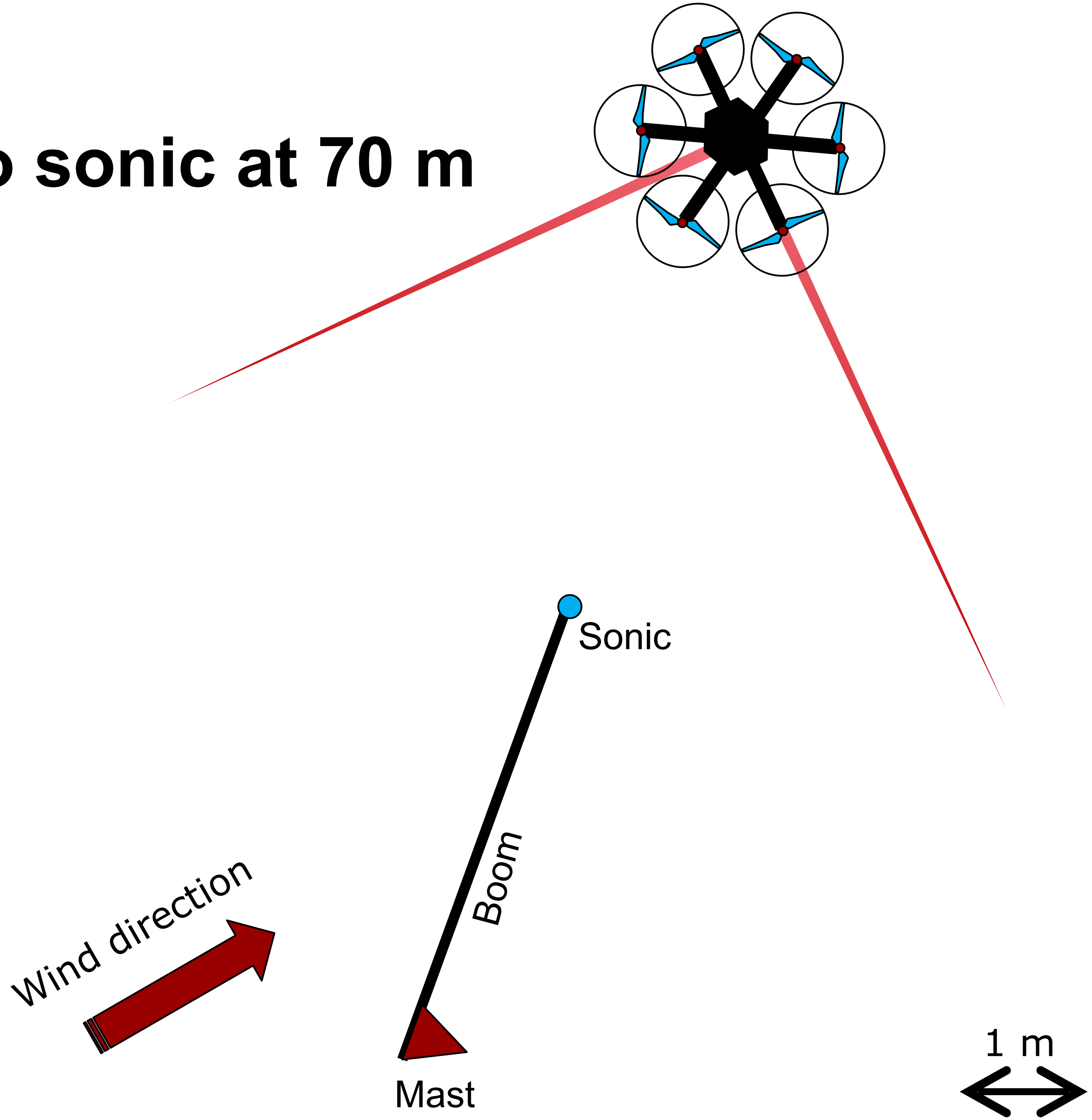
Measurements next to sonic at 70 m

V52 met mast at Risø campus

Slide source: https://zenodo.org/record/3249999

Measurements next to sonic at 70 m

V52 met mast at Risø campus



Slide source: https://zenodo.org/record/3249999

Incoming 50 Hz data

Slide source: https://zenodo.org/record/3249999

Incoming 50 Hz data

Slide source: https://zenodo.org/record/3249999

Incoming 50 Hz data

Slide source: https://zenodo.org/record/3249999

Beware

Beware

- This is a proof-of-concept stage in a product development

Beware

- This is a proof-of-concept stage in a product development
- Drone was manually positioned and maintained next to the sonic anemometer
  - RTK of Differential GPS did not work
  - We used basically our eyes and on-board + GoPro camera to work out drone position

Slide source: https://zenodo.org/record/3249999

Beware

- This is a proof-of-concept stage in a product development

- Drone was manually positioned and maintained next to the sonic anemometer
  - RTK of Differential GPS did not work
  - We used basically our eyes and on-board + GoPro camera to work out drone position

Slide source: https://zenodo.org/record/3249999

Beware

- This is a proof-of-concept stage in a product development

- Drone was manually positioned and maintained next to the sonic anemometer
  - RTK of Differential GPS did not work
  - We used basically our eyes and on-board + GoPro camera to work out drone position

- **Drone motion was not subtracted from the Doppler shift**

Slide source: https://zenodo.org/record/3249999

Beware

- This is a proof-of-concept stage in a product development
- Drone was manually positioned and maintained next to the sonic anemometer
  - RTK of Differential GPS did not work
  - We used basically our eyes and on-board + GoPro camera to work out drone position
- **Drone motion was not subtracted from the Doppler shift**
- These were not ‘co-located’ measurements

Beware

- This is a proof-of-concept stage in a product development

- Drone was manually positioned and maintained next to the sonic anemometer
  - RTK of Differential GPS did not work
  - We used basically our eyes and on-board + GoPro camera to work out drone position

- **Drone motion was not subtracted from the Doppler shift**

- These were not ‘co-located’ measurements

Slide source: https://zenodo.org/record/3249999

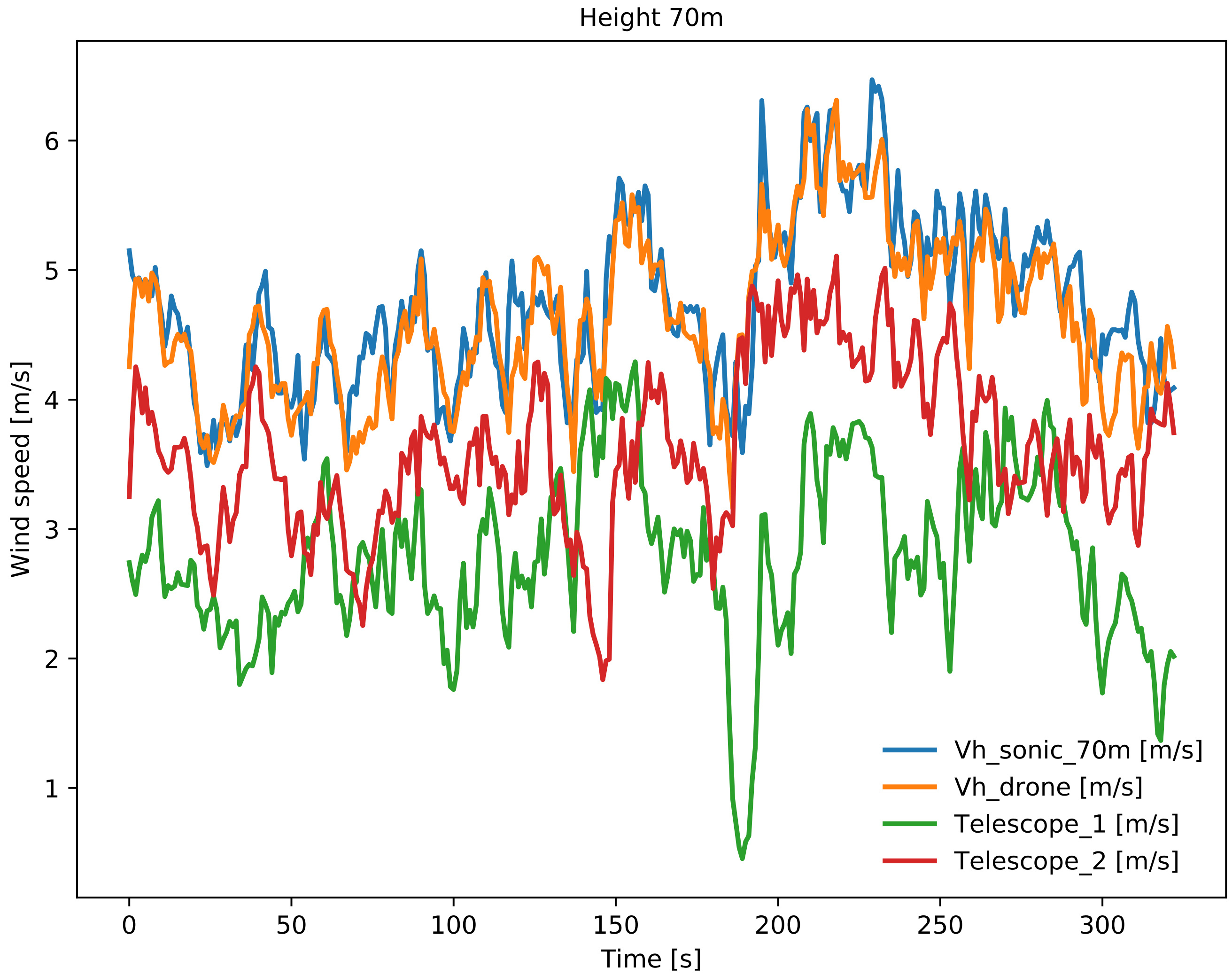
Beware

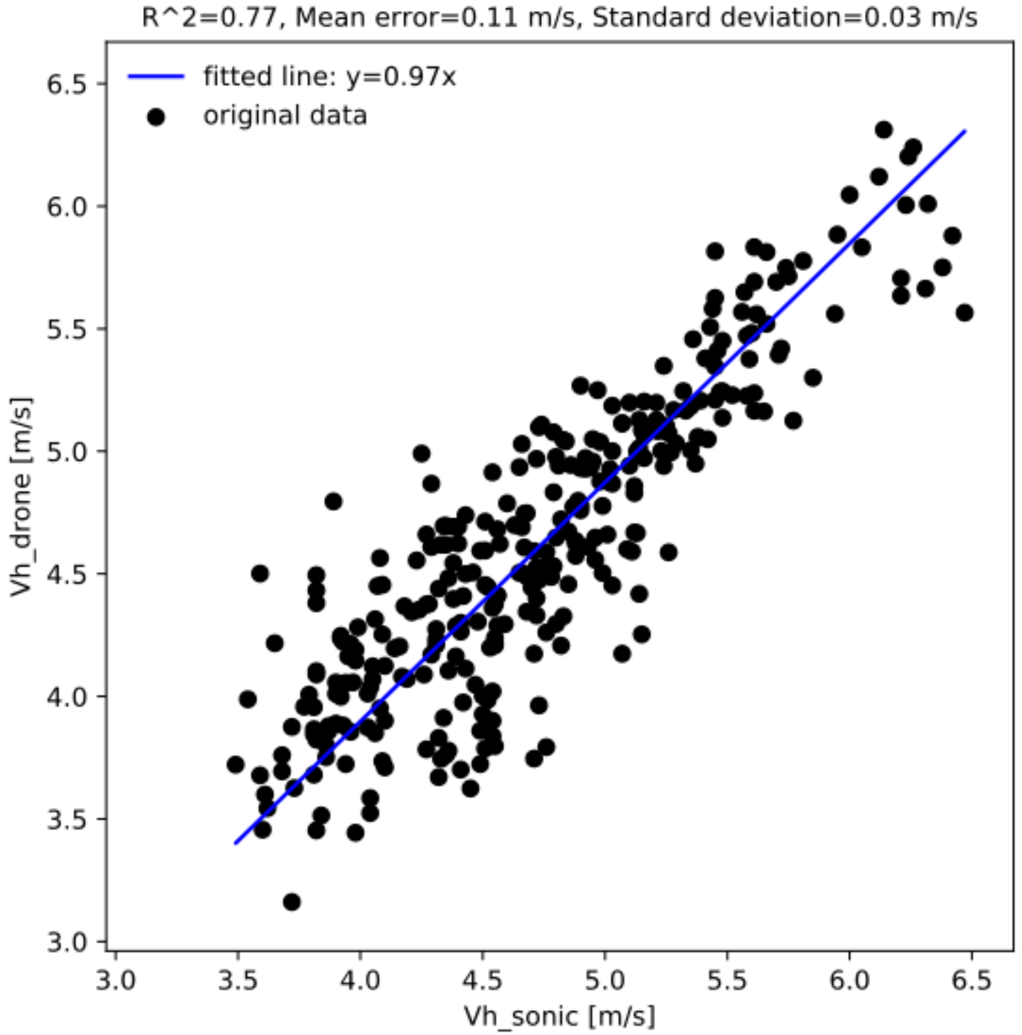
- This is a proof-of-concept stage in a product development
- Drone was manually positioned and maintained next to the sonic anemometer
  – RTK of Differential GPS did not work
  – We used basically our eyes and on-board + GoPro camera to work out drone position
- **Drone motion was not subtracted from the Doppler shift**
- These were not ‘co-located’ measurements
- You will see 1 Hz averaged data on next slide

Slide source: https://zenodo.org/record/3249999

Results (1 Hz data comparison)

Mean difference 0.11 m/s
y=0.97x
$R^2 = 0.77$





Slide source: https://zenodo.org/record/3249999

Summary

Summary

- Successfully demonstrated that:
  - Drone-lidar wind measurements are possible
  - Consistent with that measured by the nearby sonic anemometers

Slide source: https://zenodo.org/record/3249999

Summary

- Successfully demonstrated that:
  - Drone-lidar wind measurements are possible
  - Consistent with that measured by the nearby sonic anemometers

Slide source: https://zenodo.org/record/3249999

Summary

- Successfully demonstrated that:
  - Drone-lidar wind measurements are possible
  - Consistent with that measured by the nearby sonic anemometers

- Despite this being a first attempt we have already accomplished a close agreement to the nearby mast instrumentation

Slide source: https://zenodo.org/record/3249999

Summary

- Successfully demonstrated that:
  - Drone-lidar wind measurements are possible
  - Consistent with that measured by the nearby sonic anemometers

- Despite this being a first attempt we have already accomplished a close agreement to the nearby mast instrumentation

- **This has been achieved using only the basic drone position stabilization and without correcting in any way for the drone motion!**

Slide source: https://zenodo.org/record/3249999

Summary

- Successfully demonstrated that:
  - Drone-lidar wind measurements are possible
  - Consistent with that measured by the nearby sonic anemometers

- Despite this being a first attempt we have already accomplished a close agreement to the nearby mast instrumentation

- **This has been achieved using only the basic drone position stabilization and without correcting in any way for the drone motion!**

- We done a bit more in December 2018 than what is showed in slides

Slide source: https://zenodo.org/record/3249999

Summary

- Successfully demonstrated that:
  - Drone-lidar wind measurements are possible
  - Consistent with that measured by the nearby sonic anemometers
- Despite this being a first attempt we have already accomplished a close agreement to the nearby mast instrumentation
- **This has been achieved using only the basic drone position stabilization and without correcting in any way for the drone motion!**
- We done a bit more in December 2018 than what is showed in slides

Summary

- Successfully demonstrated that:
  - Drone-lidar wind measurements are possible
  - Consistent with that measured by the nearby sonic anemometers

- Despite this being a first attempt we have already accomplished a close agreement to the nearby mast instrumentation

- **This has been achieved using only the basic drone position stabilization and without correcting in any way for the drone motion!**

- We done a bit more in December 2018 than what is showed in slides

- Currently a paper describing the results under review in AMT: https://www.atmos-meas-tech-discuss.net/amt-2019-102/

Future work

Future work

- Since the POC results are encouraging, we will proceed and enter in the phase of prototyping

Future work

- Since the POC results are encouraging, we will proceed and enter in the phase of prototyping
- Explore both a fully tethered (optic and power link physically attached to the drone), non-tethered (battery powered drone and entire lidar(s) mounted on the drone), and hybrid (battery power drone and telescopes attached to the drone/gimbal) concepts

Slide source: https://zenodo.org/record/3249999

Future work

- Since the POC results are encouraging, we will proceed and enter in the phase of prototyping
- Explore both a fully tethered (optic and power link physically attached to the drone), non-tethered (battery powered drone and entire lidar(s) mounted on the drone), and hybrid (battery power drone and telescopes attached to the drone/gimbal) concepts
- Build a compact-form low-power data acquisition and control system (DACS) based on Raspberry Pi, where the DACS software will be based on Python

Slide source: https://zenodo.org/record/3249999

Future work

- Since the POC results are encouraging, we will proceed and enter in the phase of prototyping
- Explore both a fully tethered (optic and power link physically attached to the drone), non-tethered (battery powered drone and entire lidar(s) mounted on the drone), and hybrid (battery power drone and telescopes attached to the drone/gimbal) concepts
- Build a compact-form low-power data acquisition and control system (DACS) based on Raspberry Pi, where the DACS software will be based on Python
- Develop the uncertainty model for the drone-based wind lidar system based on the GUM methodology Joint Committee for Guides in Metrology (2008)

Slide source: https://zenodo.org/record/3249999

Future work

- Since the POC results are encouraging, we will proceed and enter in the phase of prototyping
- Explore both a fully tethered (optic and power link physically attached to the drone), non-tethered (battery powered drone and entire lidar(s) mounted on the drone), and hybrid (battery power drone and telescopes attached to the drone/gimbal) concepts
- Build a compact-form low-power data acquisition and control system (DACS) based on Raspberry Pi, where the DACS software will be based on Python
- Develop the uncertainty model for the drone-based wind lidar system based on the GUM methodology Joint Committee for Guides in Metrology (2008)
- In accordance to the uncertainty model we will propose testing and calibration procedures

Slide source: https://zenodo.org/record/3249999

Future work

- Since the POC results are encouraging, we will proceed and enter in the phase of prototyping
- Explore both a fully tethered (optic and power link physically attached to the drone), non-tethered (battery powered drone and entire lidar(s) mounted on the drone), and hybrid (battery power drone and telescopes attached to the drone/gimbal) concepts
- Build a compact-form low-power data acquisition and control system (DACS) based on Raspberry Pi, where the DACS software will be based on Python
- Develop the uncertainty model for the drone-based wind lidar system based on the GUM methodology Joint Committee for Guides in Metrology (2008)
- In accordance to the uncertainty model we will propose testing and calibration procedures
- Demonstrate new measurement technique in various applications ranging from wind energy, wind engineering to sports and leisure

Slide source: https://zenodo.org/record/3249999

Acknowledgment

- NCAR and NSF for providing funding for my visit as a part of Robert Menke's ASP fellowship
- RECAST project for resources for *campaign-planning-tool* development
- DTU Wind Energy for internal funding for the drone-based wind lidar development

Thank you for your attention
Questions?

niva@dtu.dk