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Publication date:
2014

Document Version
Peer reviewed version

TSARS 2014 28-31 Jan

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ASSESSMENT AND IMPROVEMENT OF A SCANNING LIDAR LASER BEAM POSITIONING ACCURACY

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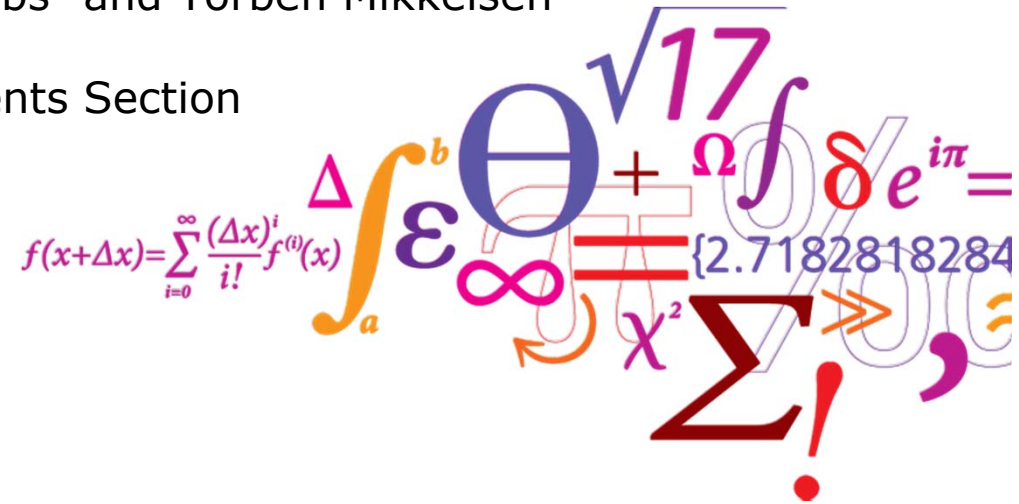
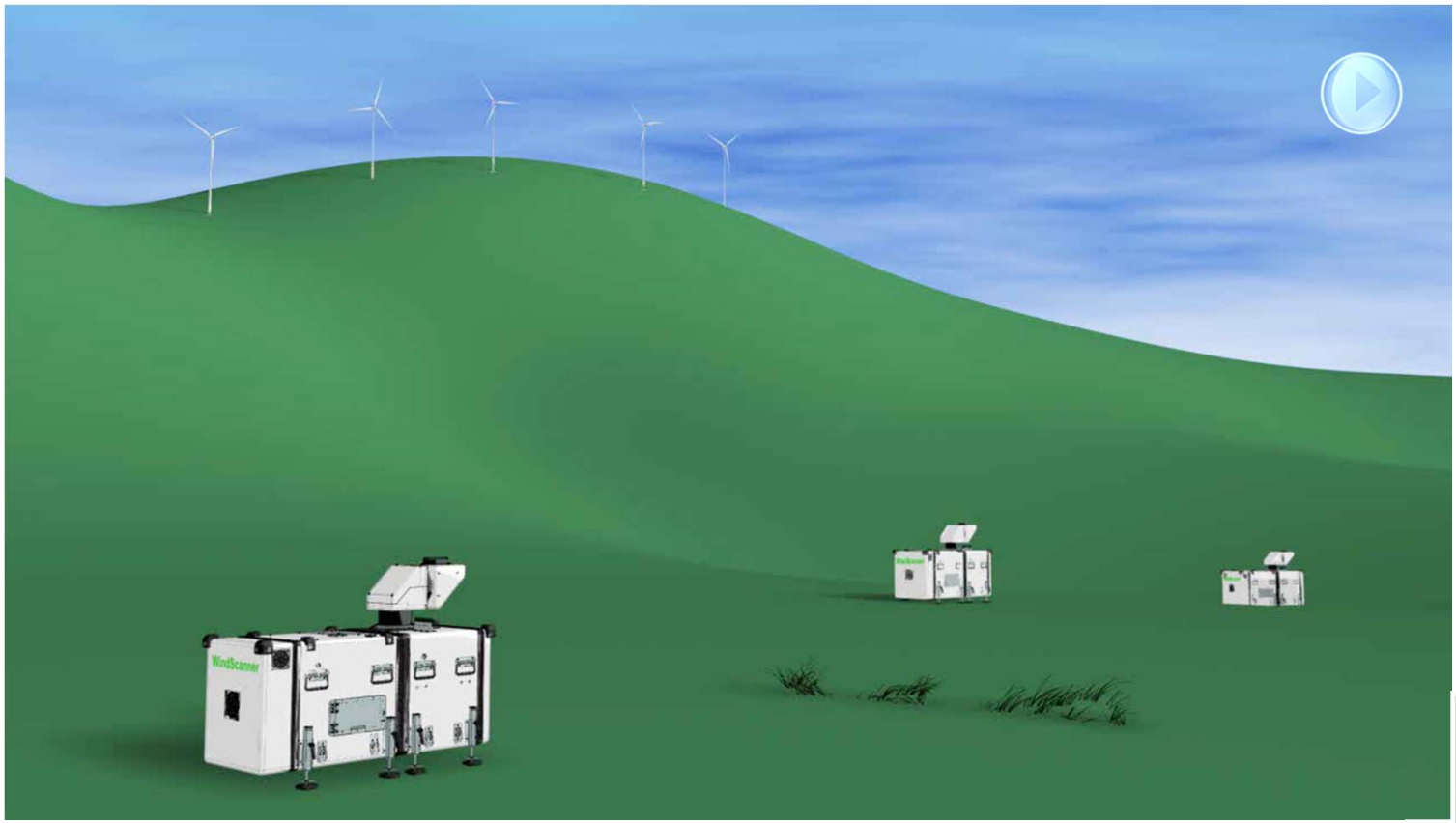


DTU Wind Energy
Department of Wind Energy

Heason Technology Limited

DELTA TAU

Motivation



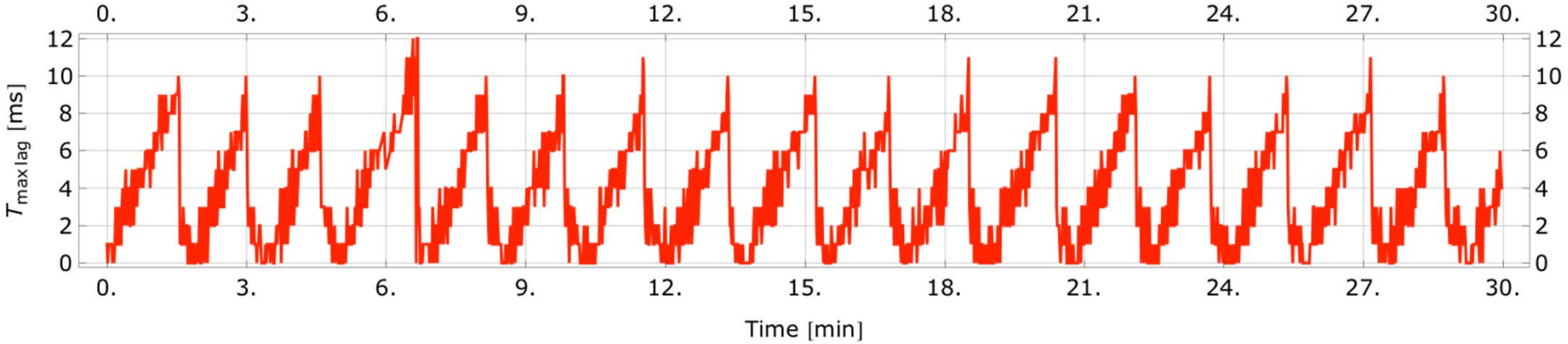
Master computer

- Long-range WindScanner system
- Unified system of multiple pulsed coherent Doppler scanning lidars
- Lidars are intended to be **time-space** synchronized

Time synchronization

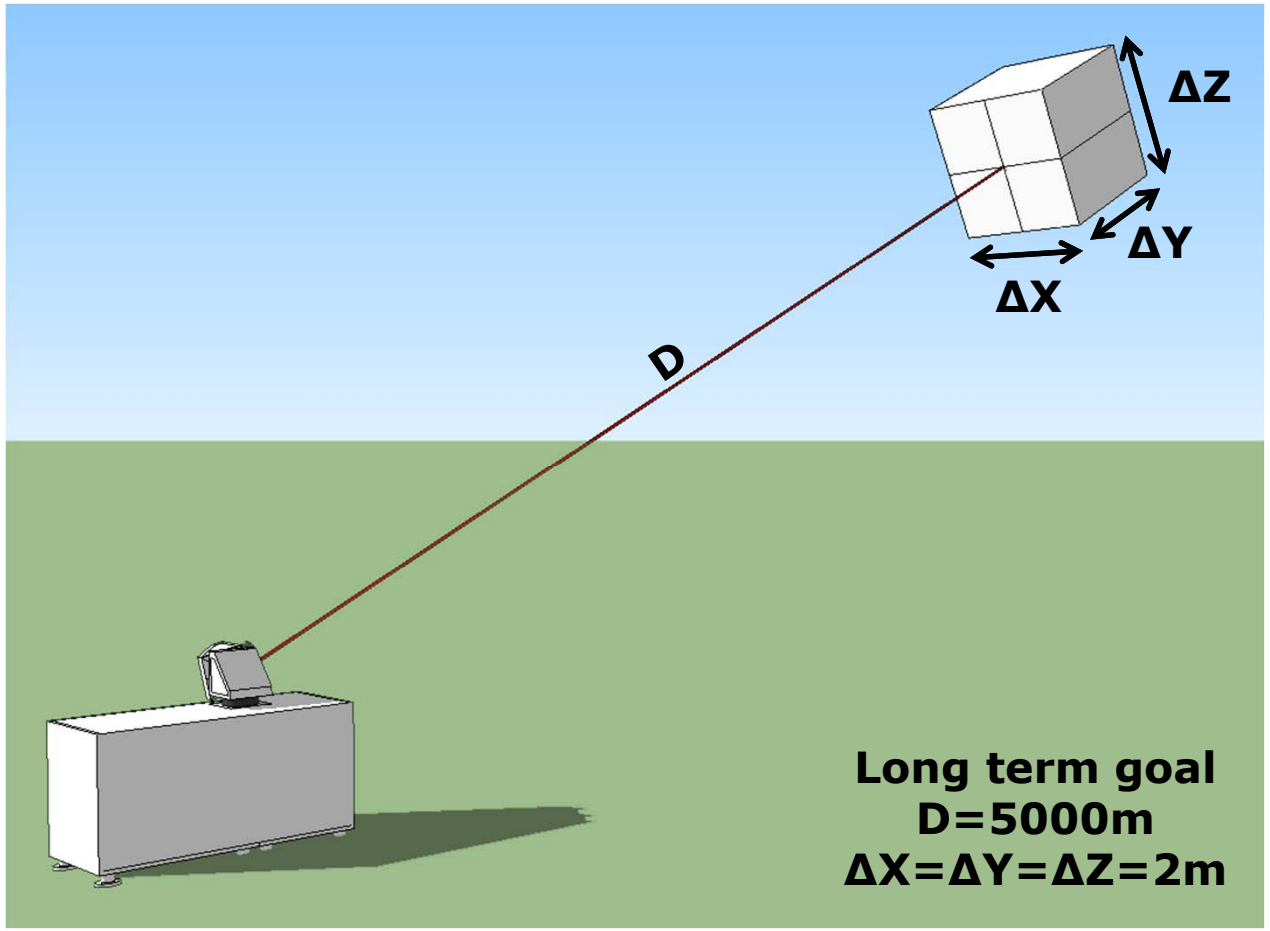
Max lag 10 ms [1] irrespective to:
- Measurement time
- Number of lidars

The maximum lag



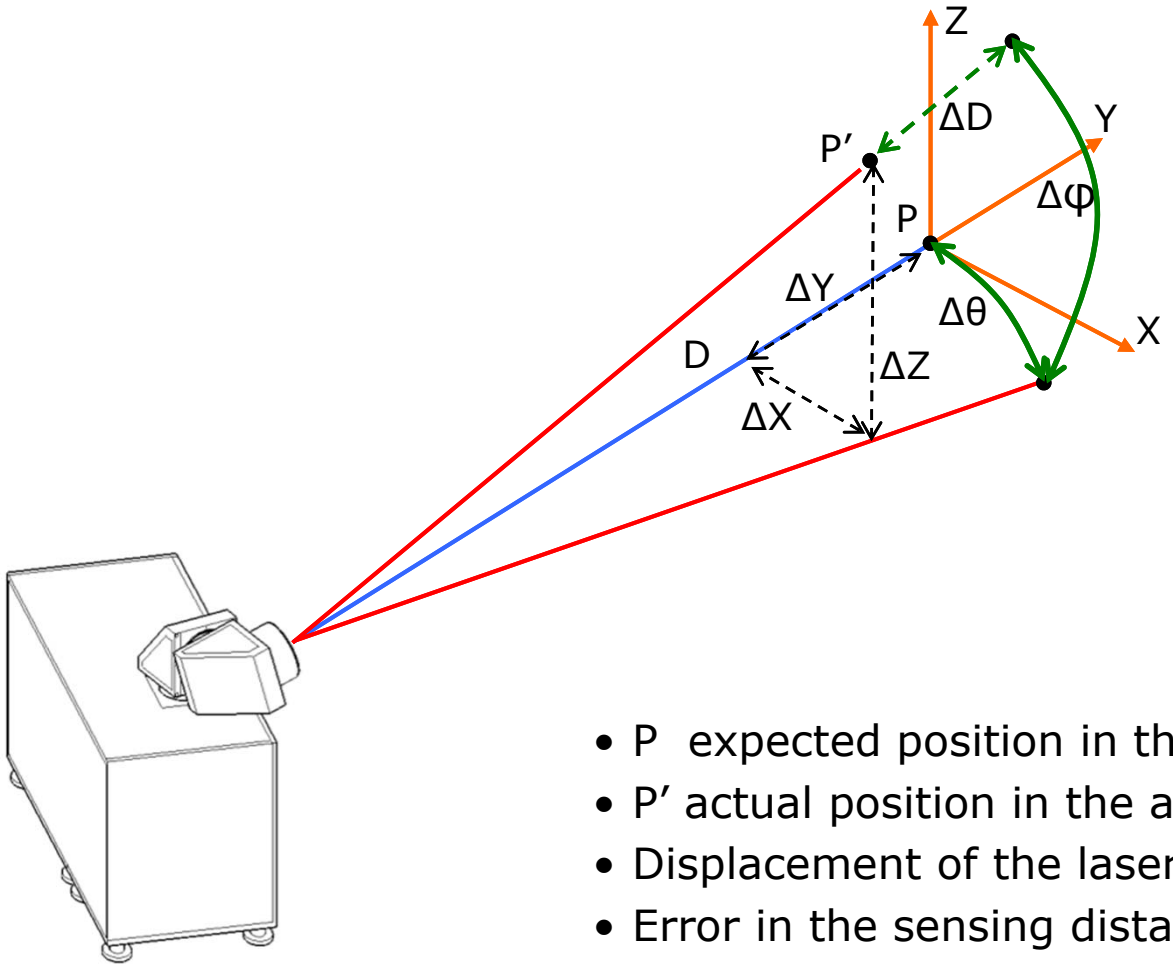
[1] Vasiljević, N. et al. (2013). *"The long-range WindScanner system – how to synchronously intersect multiple laser beams"*

Space synchronization



- Cube represents the volume in which we expect the center of range gate

Uncertainty in laser beam positioning



- P expected position in the atmosphere
- P' actual position in the atmosphere
- Displacement of the laser beam direction (Δθ,Δφ)
- Error in the sensing distance (ΔD)

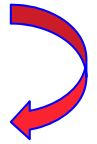
Long term goal:
Δθ=Δφ=±0.01°
ΔD=±1m

Contributors to uncertainty

ΔD

- Error in the measurements of laser pulse time of flight

- Position readings of the scanner head from the motor side
- Mechanical imperfections of the movable parts of the scanner head
- Gear backlash



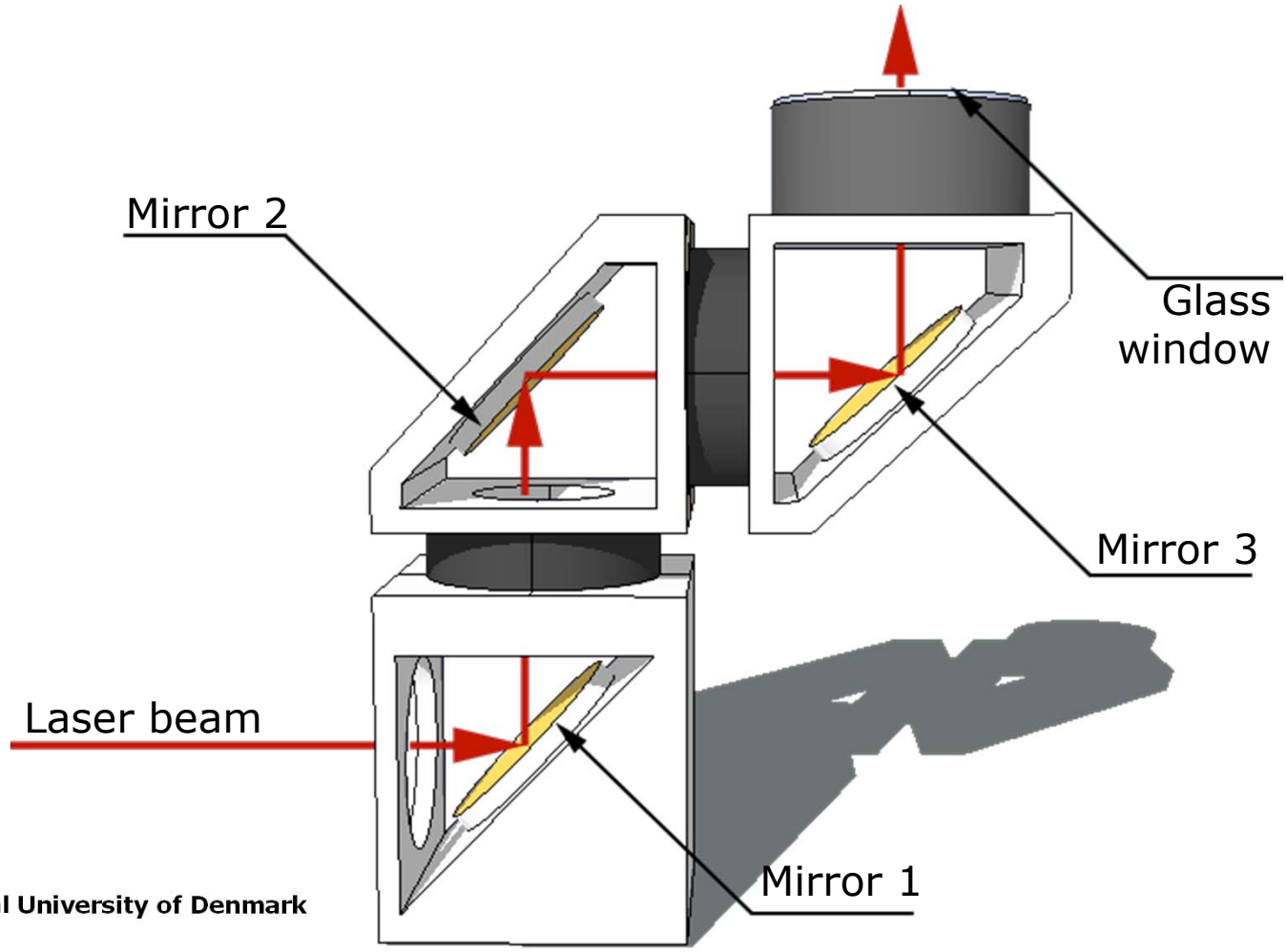
- Perpendicularity of the axes of the rotation
- Connection of the scanner head with the casing
- Dynamics of the lidar

Δθ,Δφ

- Flatness of the mirrors surfaces
- Consistency of the reflective index of the mirrors surface and the glass window of the scanner head
- Alignment of the optical components
- Home position of the scanner head
- Leveling of the lidar during measurements
- Refractive index of the atmosphere

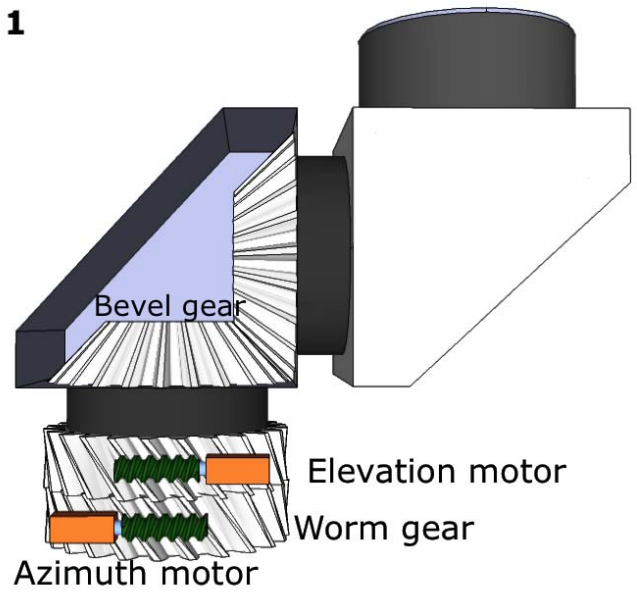
Scanner head

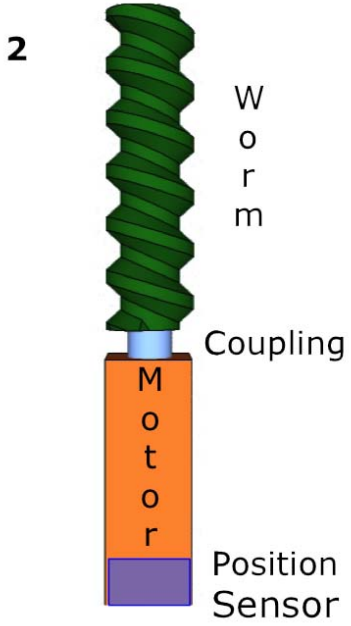
- Mirror-based steering

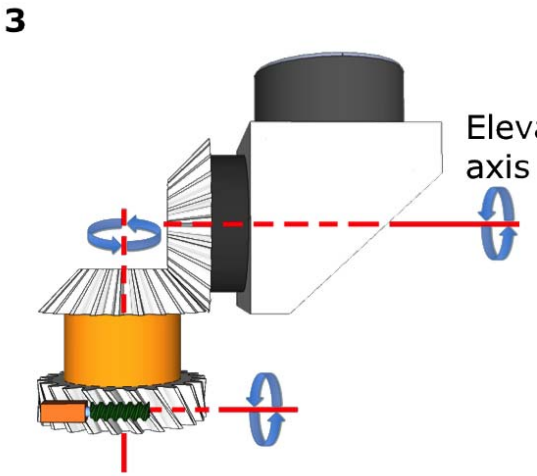


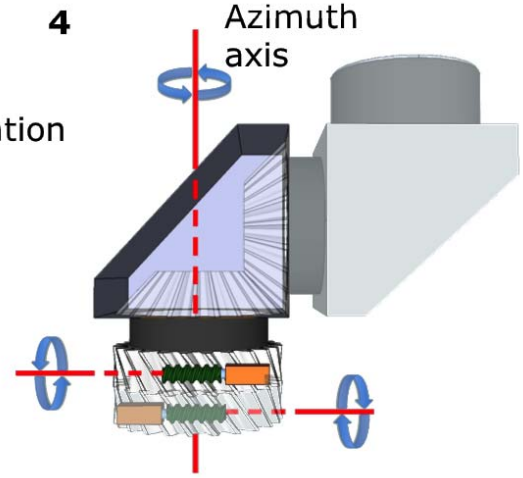
Scanner head

- Mirror-based steering
- Endless rotation
- Gear-box driven:
  - Worm
  - Worm gear
  - Bevel gears
  - …
- Position sensors = motor encoders
- Max speed 50°/s
- Max acceleration 100°/s²
- Resolution 0.0001°
- IP65
- Design and Development by DTU Wind Energy and Steen Andreasen (IPU)



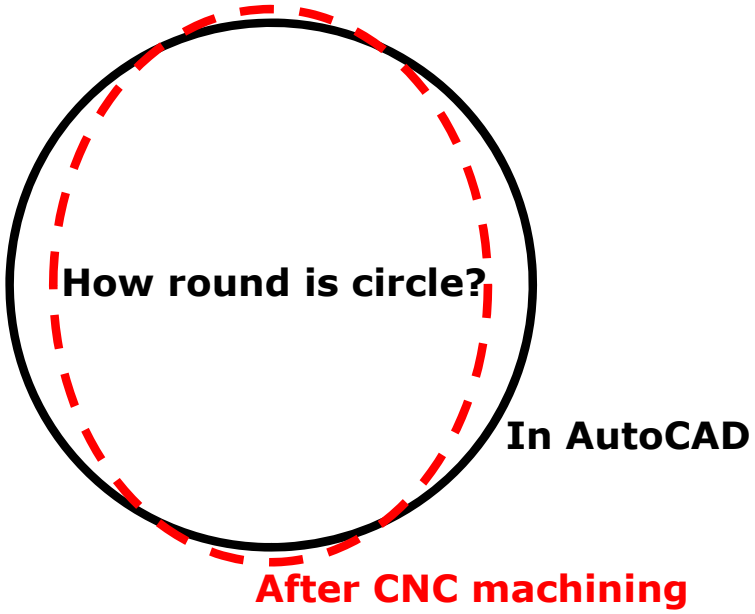




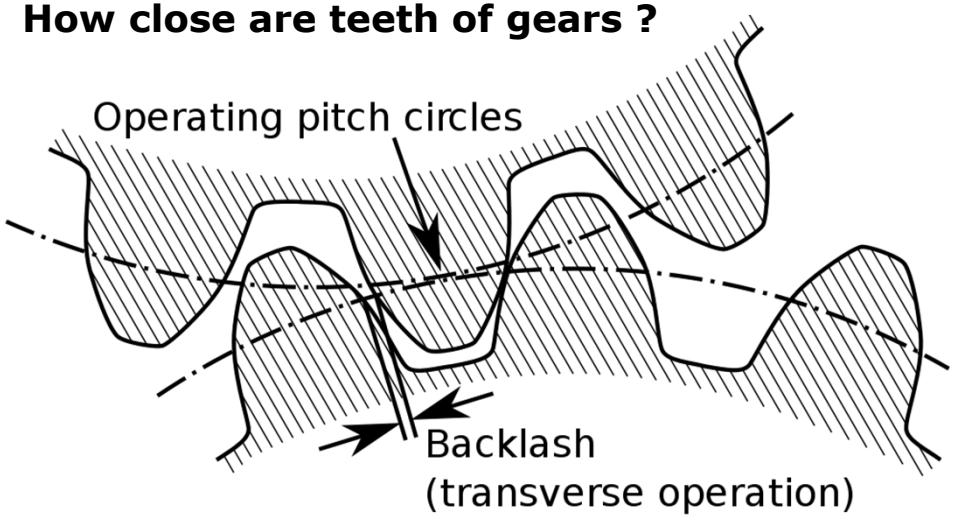


Issues with design

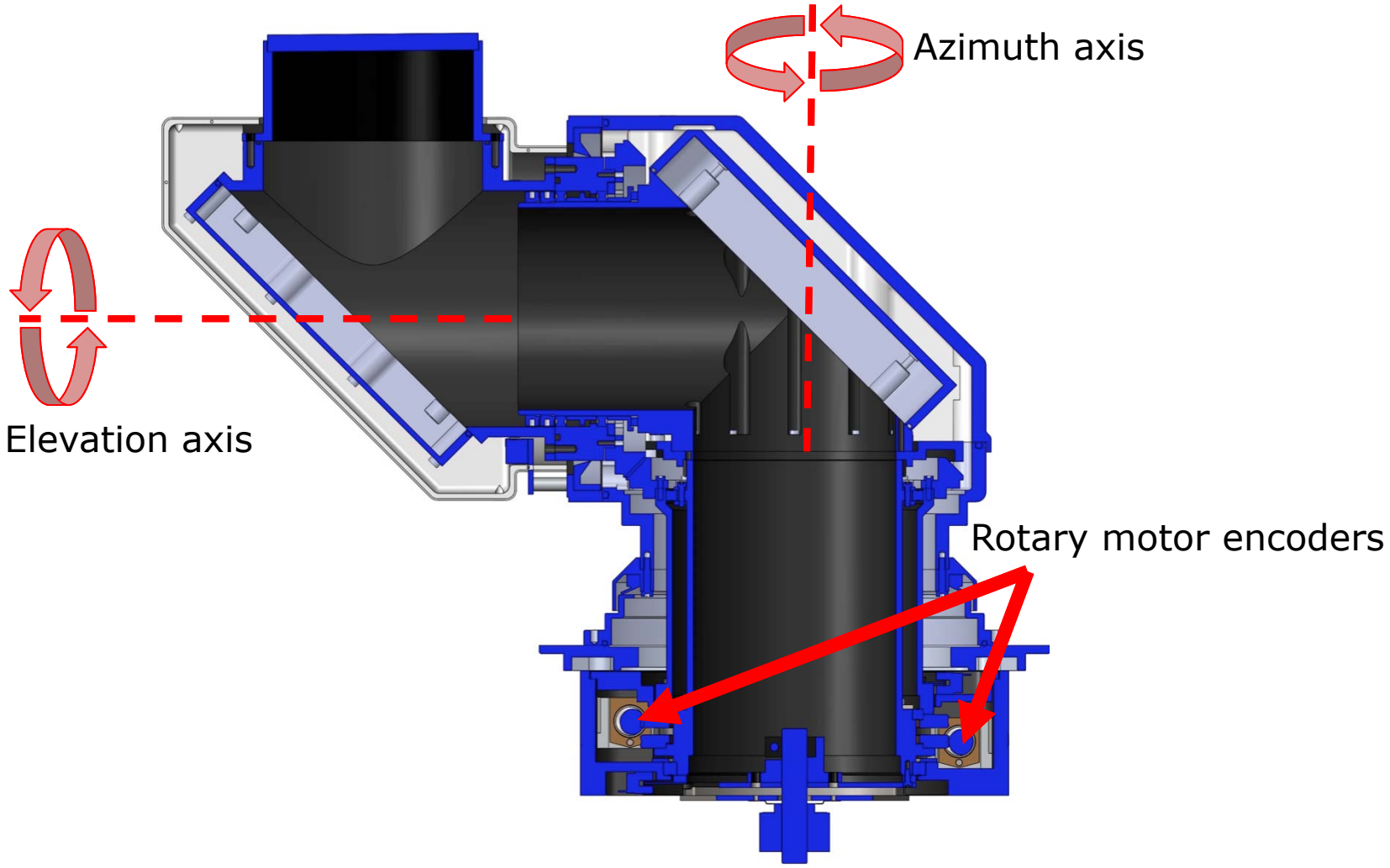
- Tolerances in manufacturing of gear-box components
- Unavoidable backlash
- Position readings from the motor side do not necessary correspond to the actual positions of the scanner head



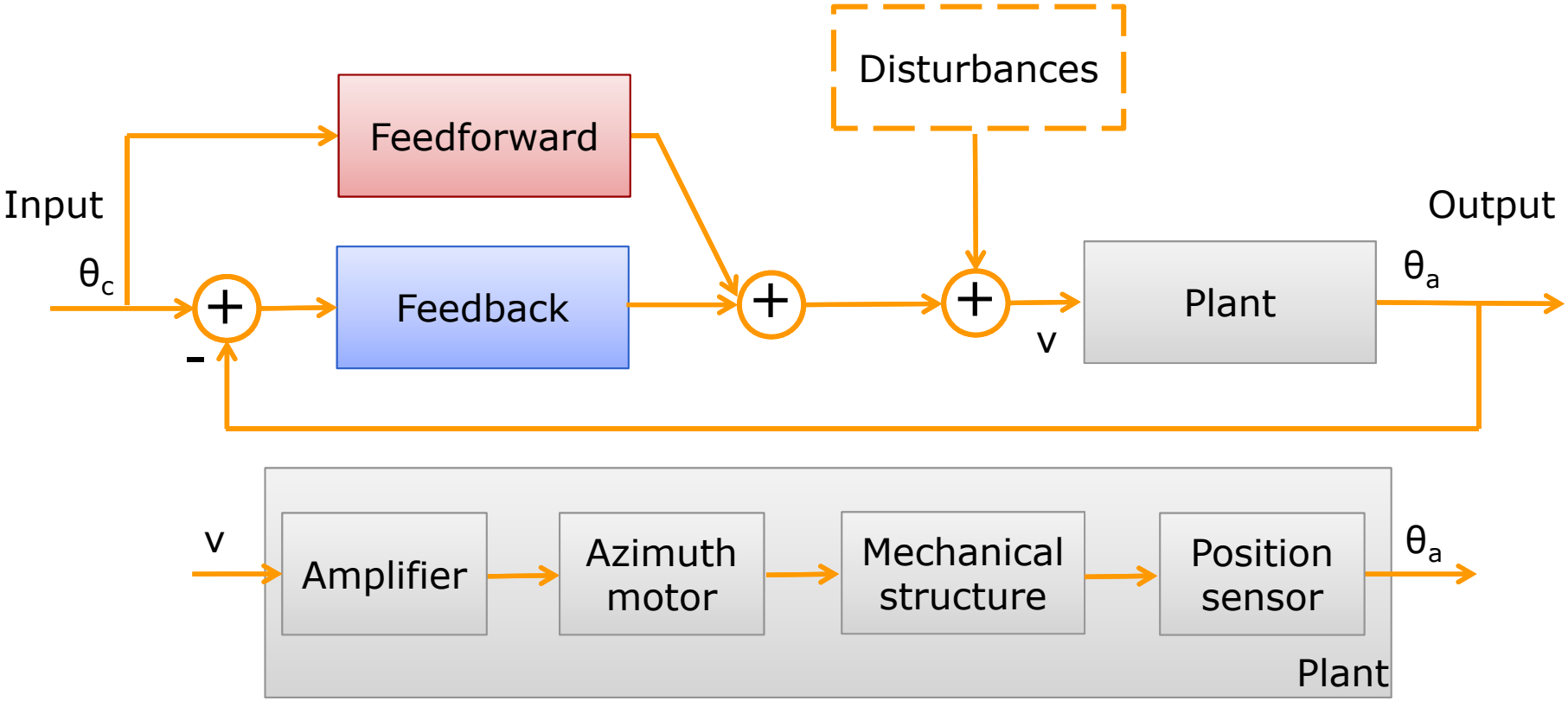
How close are teeth of gears ?



Why don’t they correspond?



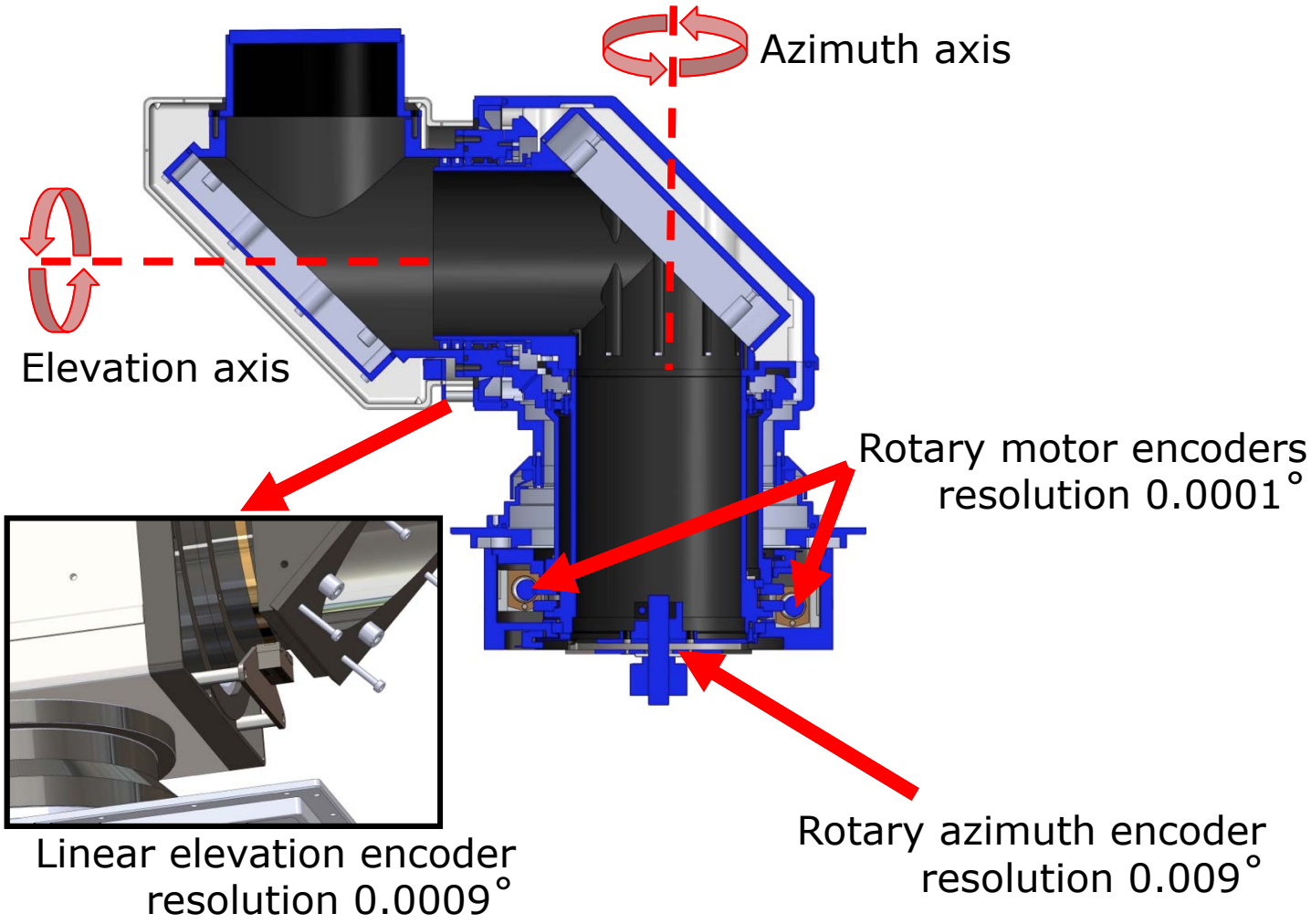
Consequences



- **Feedback and feedforward parameters cannot be accurately tuned**
- **Feedback control will not have complete information**

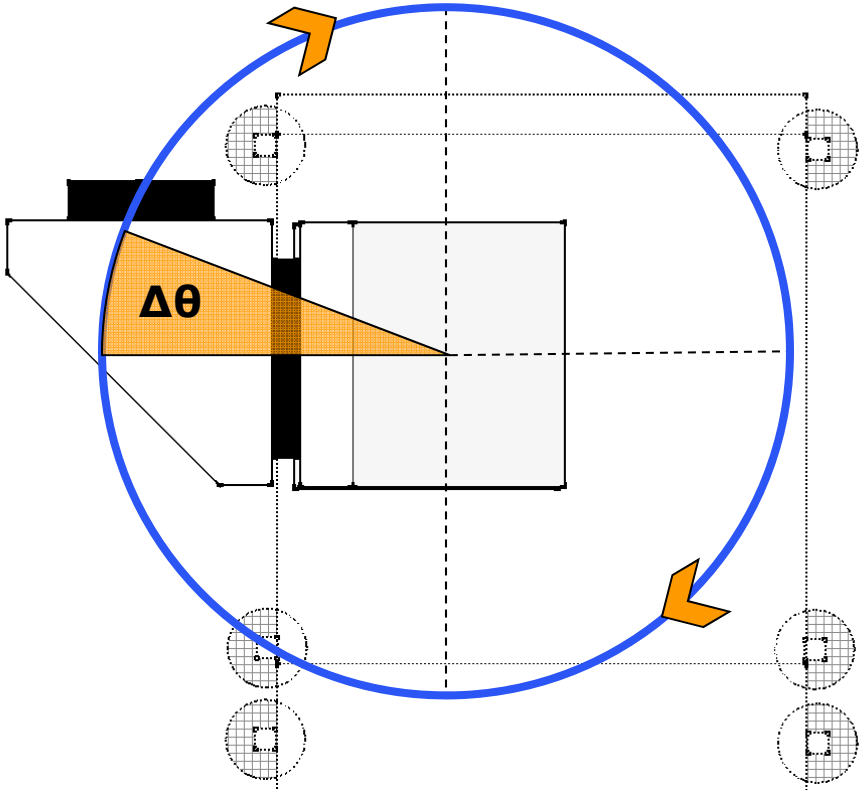
=> **<u>This will reflect on the laser beam positioning accuracy!!!</u>**

Additional sensors



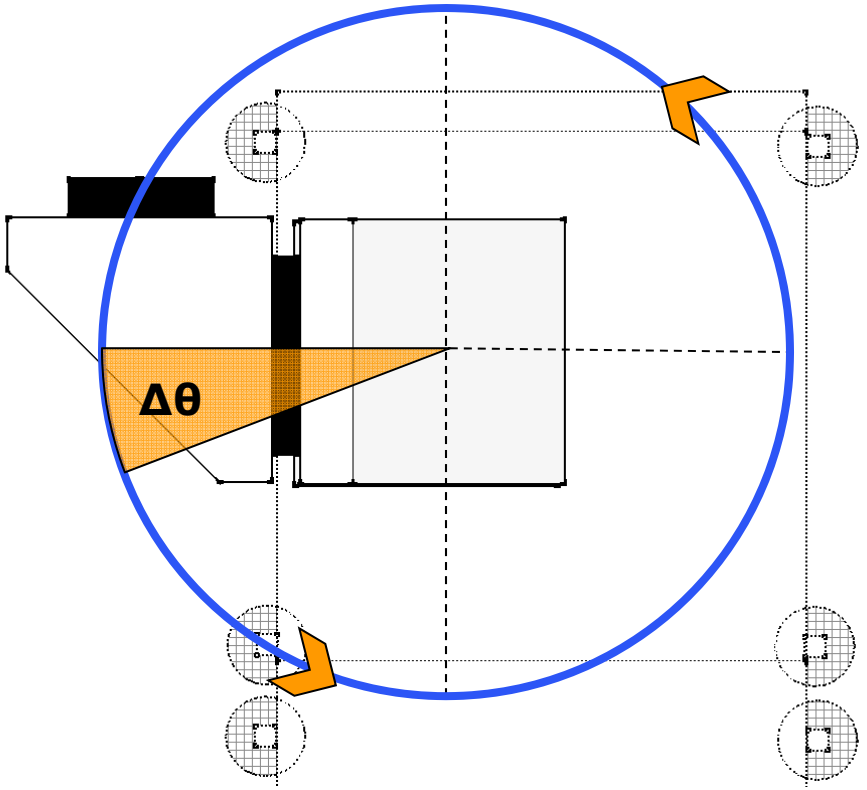
Azimuth axis test

- Clockwise rotation
- Rotate the scanner head in $\Delta\theta=10^{\circ}$ discrete moves for full 360°
- Wait for a few seconds for the scanner head to settle down
- Switch off the motor power
- Take the positions:
  - Commanded
  - Motor side
  - Load side (Actual)
- Calculate tracking errors:
  Commanded – Motor position
  Commanded – Load position

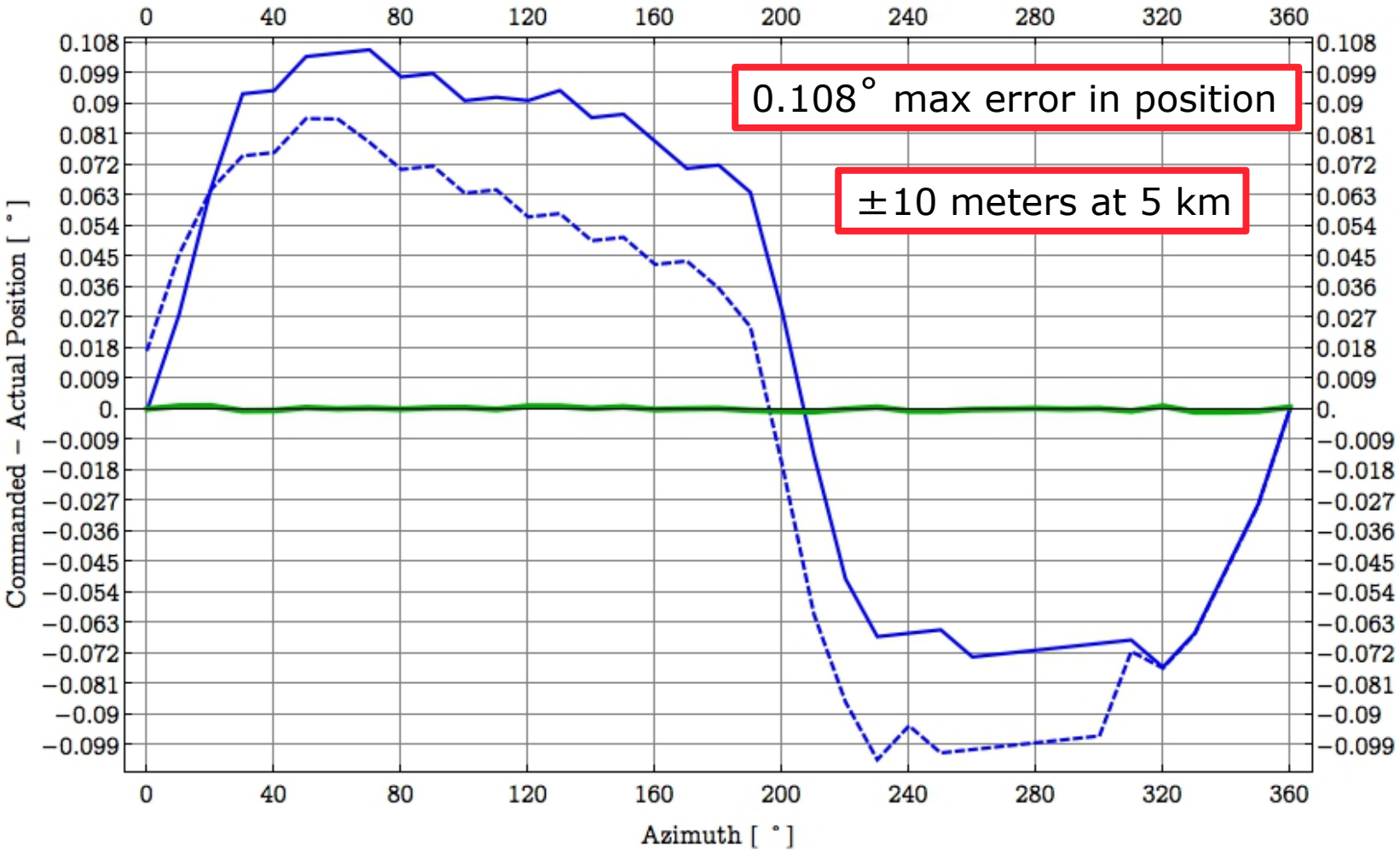


Azimuth axis test

- Anticlockwise rotation
- Rotate the scanner head in $\Delta\theta=10^{\circ}$ discrete moves for full 360°
- Wait for a few seconds for the scanner head to settle down
- Switch off the motor power
- Take the positions:
  - Commanded
  - Motor side
  - Load side (Actual)
- Calculate tracking errors:
  Commanded – Motor position
  Commanded – Load position

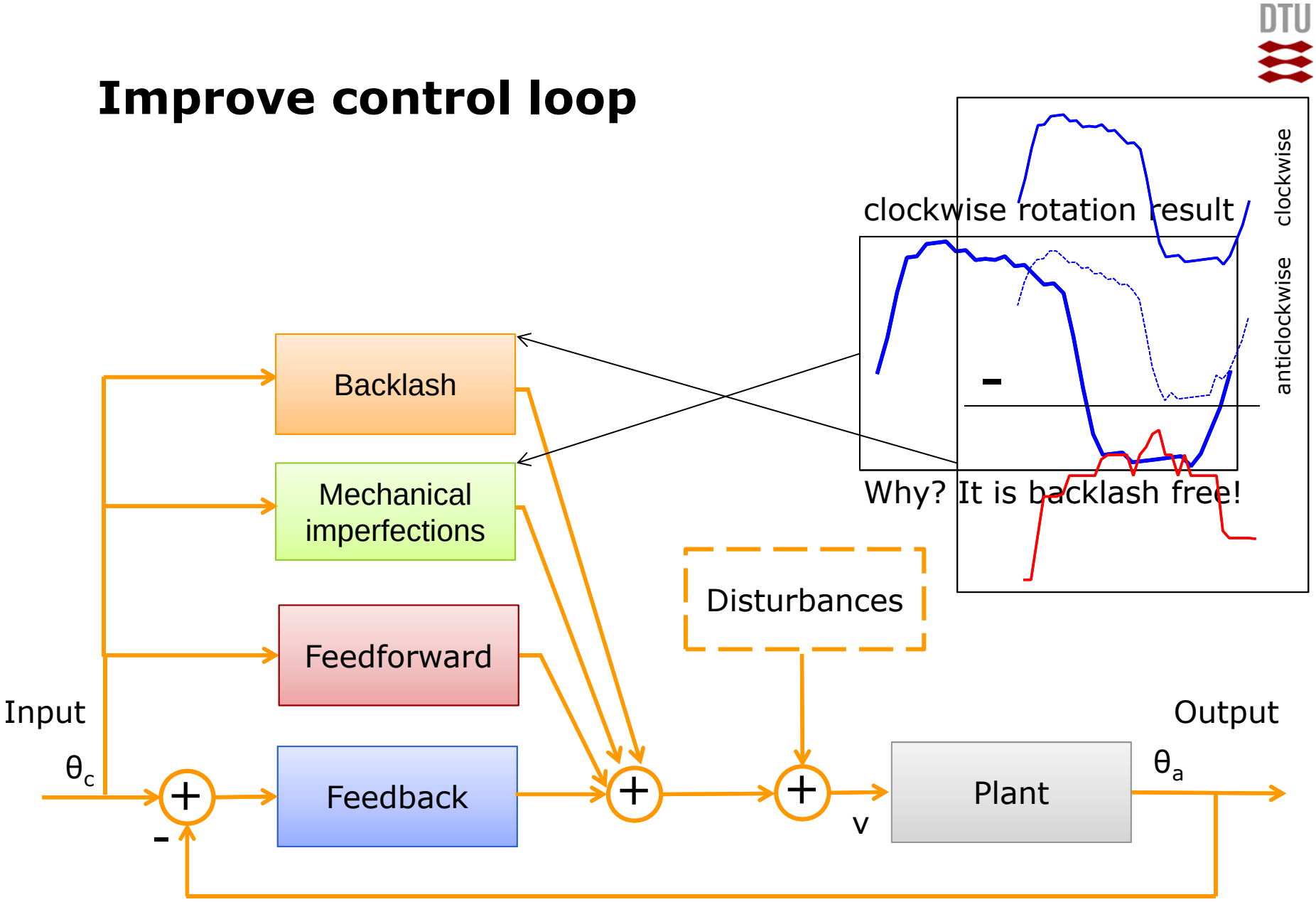


Azimuth test results

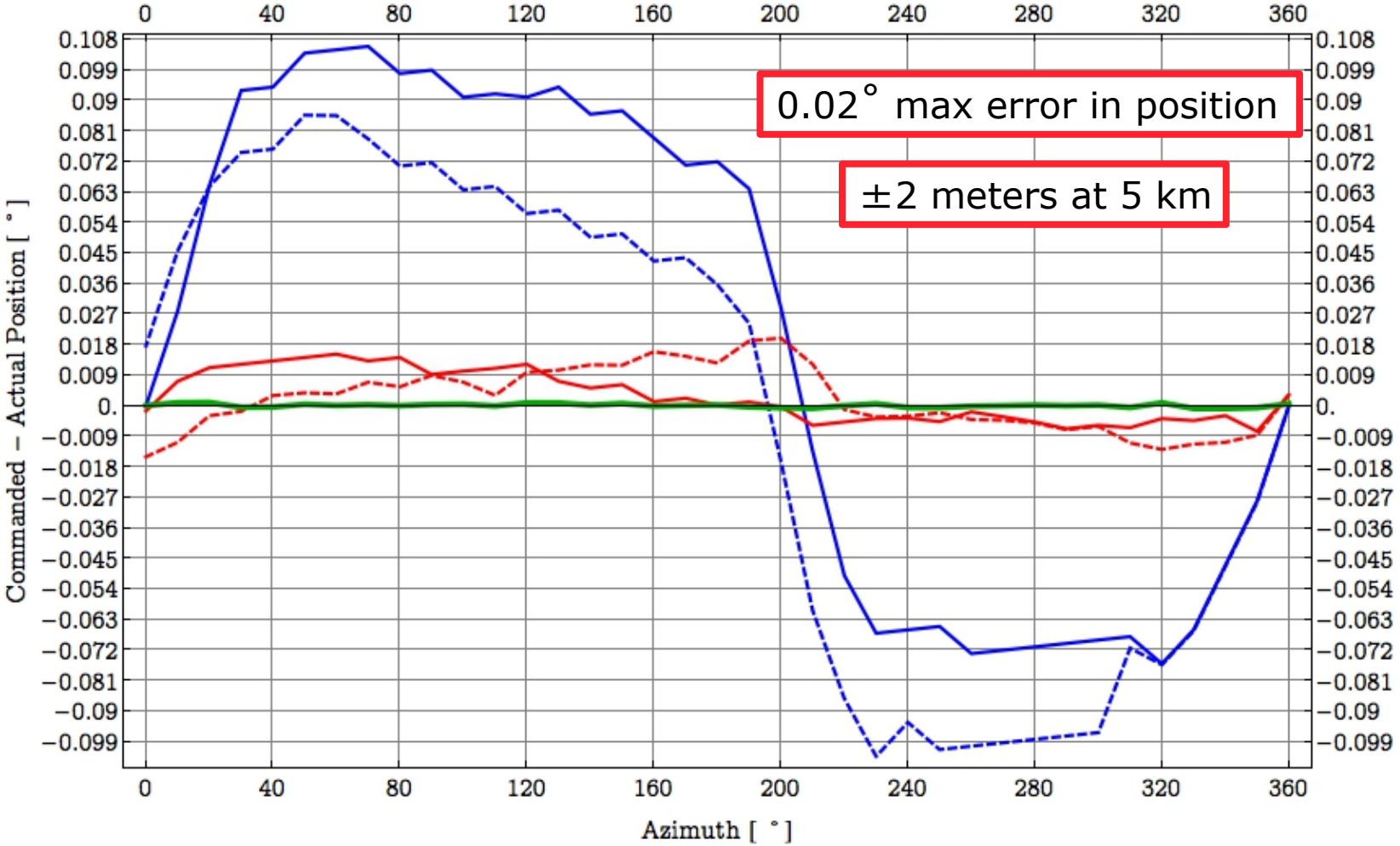


- **Solid blue line**: Commanded Position – Load Position (clockwise rotation)
- **Dashed blue line**: Commanded Position – Load Position (anticlockwise rotation)
- **Solid green line**: Commanded Position – Motor Position (bidirectional)

Improve control loop

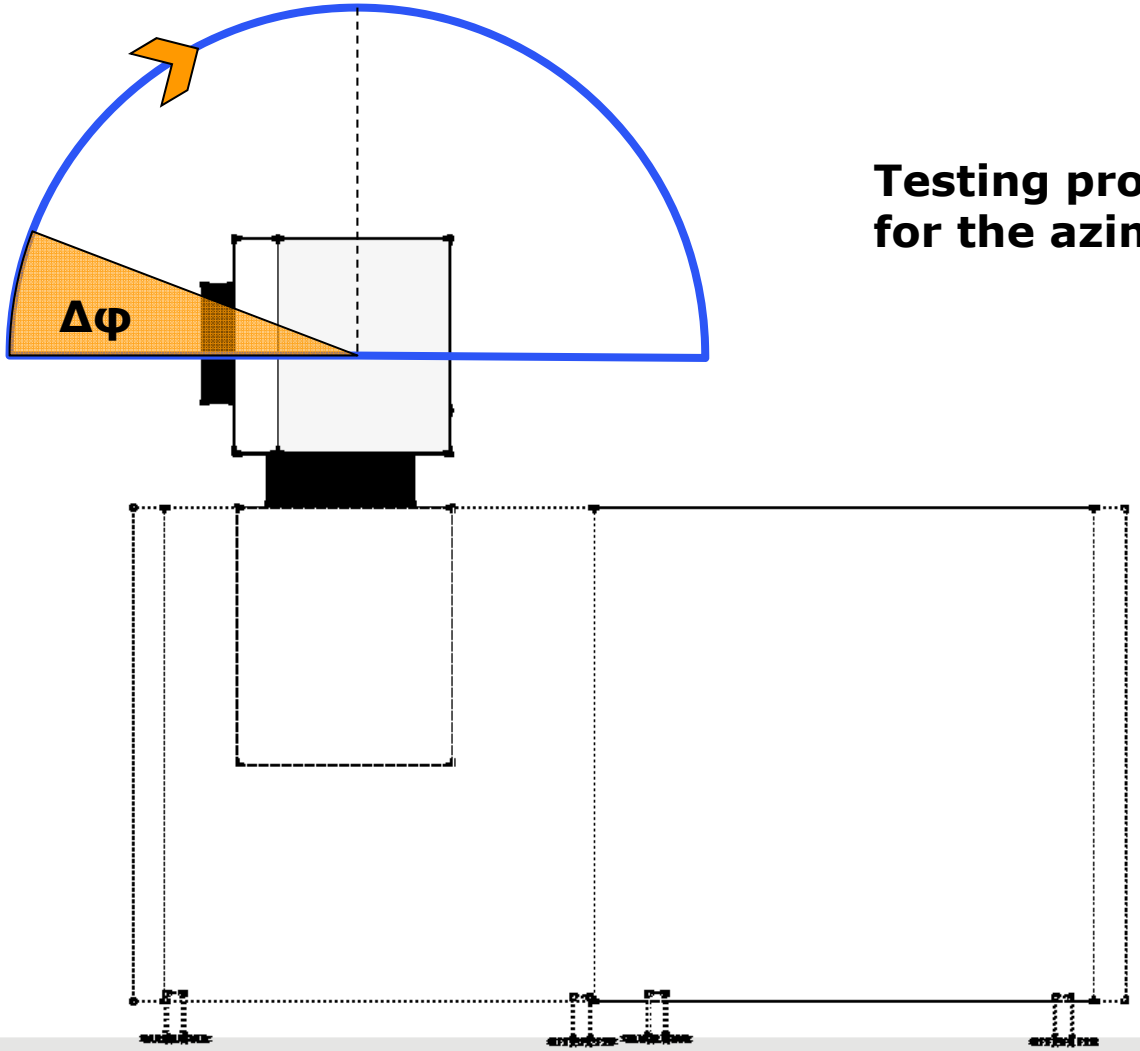


New results



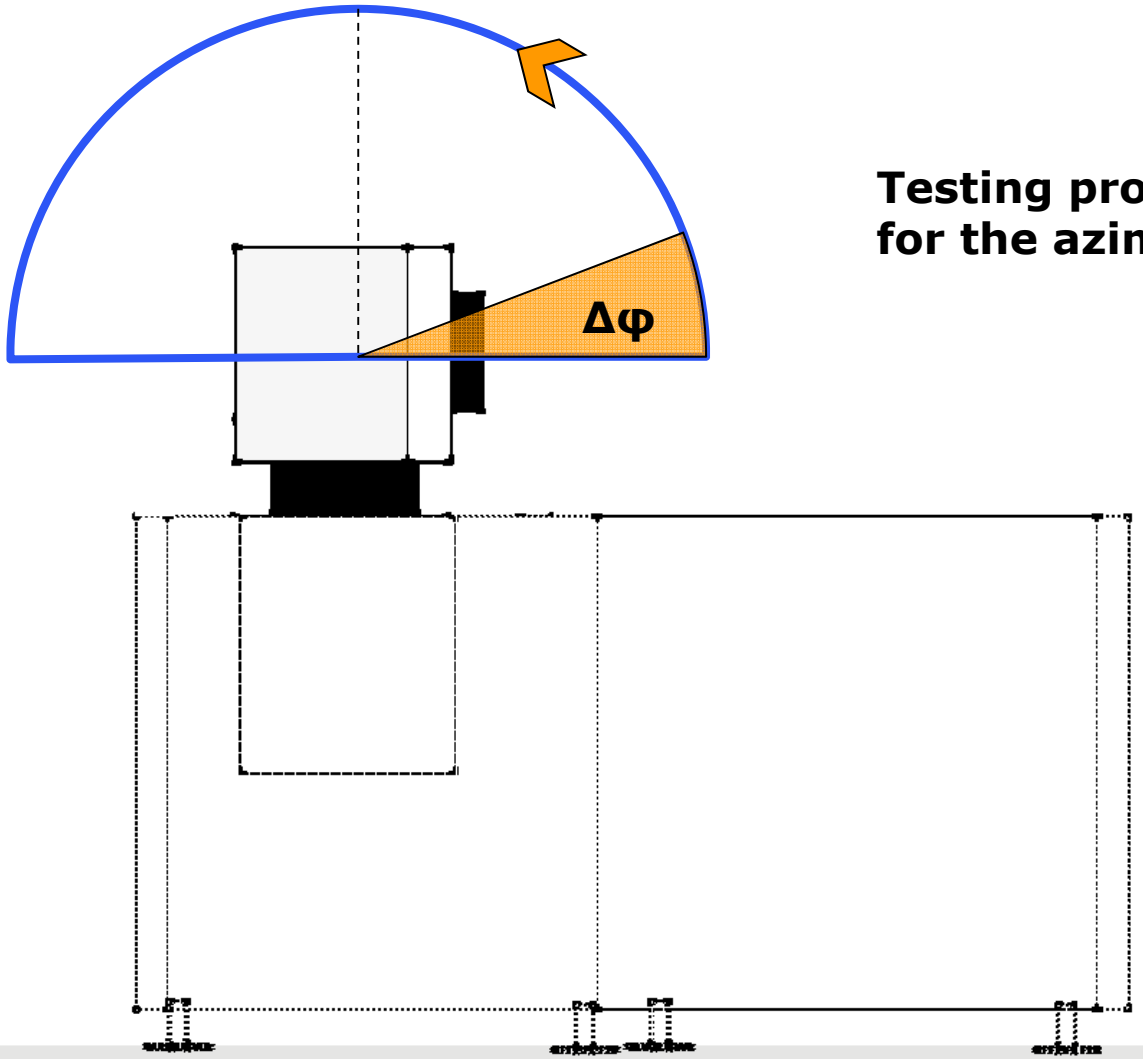
- **Solid red line**: Commanded Position – Load Position (clockwise rotation with improved control loop)
- **Dashed red line**: Commanded Position – Load Position (anticlockwise rotation with improved control loop)
- **Solid blue line**: Commanded Position – Load Position (clockwise rotation)
- **Dashed blue line**: Commanded Position – Load Position (anticlockwise rotation)
- **Solid green line**: Commanded Position – Motor Position (bidirectional)

Elevation axis test – clockwise



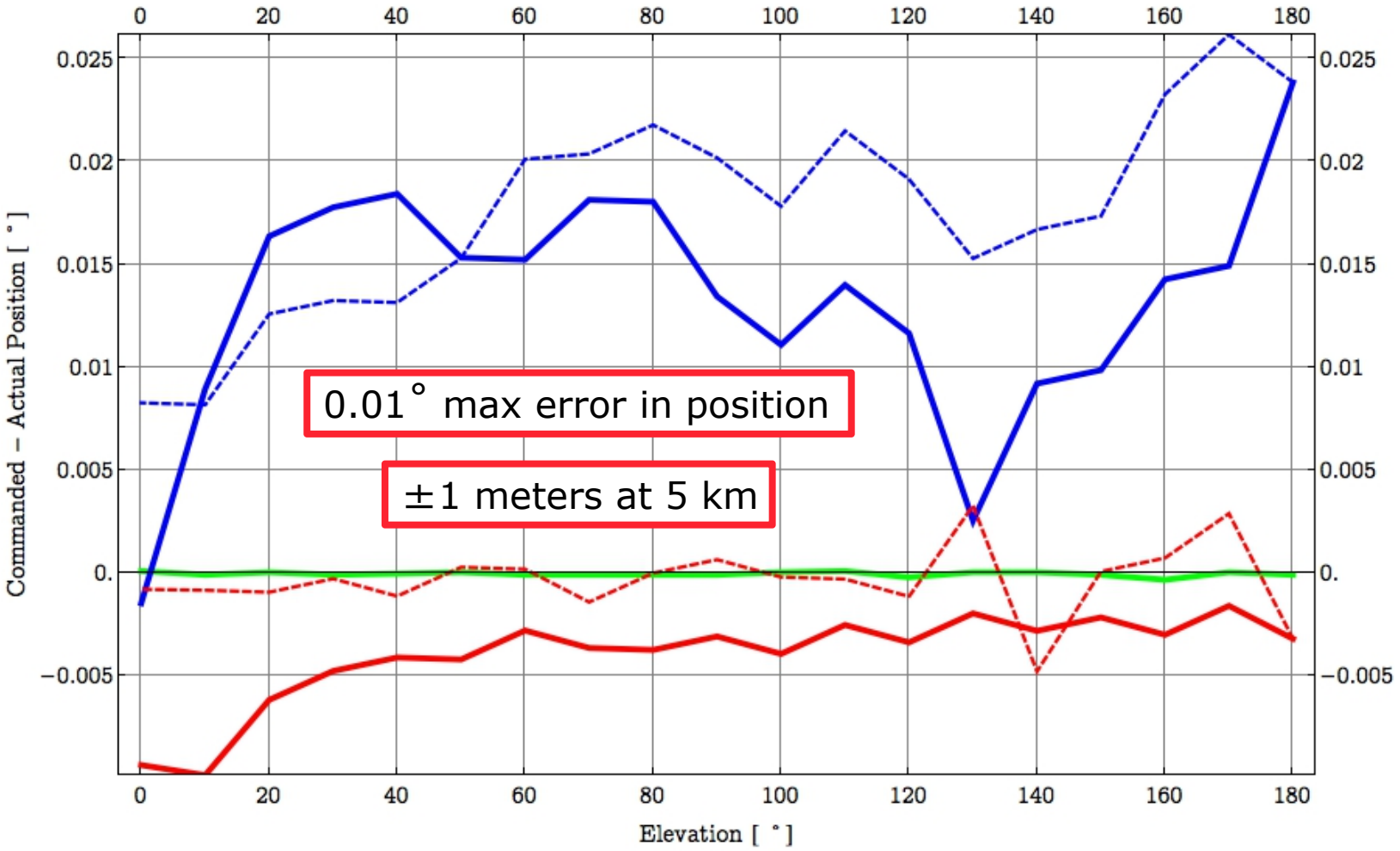
Testing procedure same as for the azimuth axis

Elevation axis test – anticlockwise



Testing procedure same as for the azimuth axis

Elevation results



- **Solid red line**: Commanded Position – Load Position (clockwise rotation with improved control loop)
- **Dashed red line**: Commanded Position – Load Position (anticlockwise rotation with improved control loop)
- **Solid blue line**: Commanded Position – Load Position (clockwise rotation)
- **Dashed blue line**: Commanded Position – Load Position (anticlockwise rotation)
- **Solid green line**: Commanded Position – Motor Position (bidirectional)

Conclusion

- Position readings from the motor side are killer factor for the accuracy
- If you can, always acquire position of the scanner head from the load side:
  - Option 1 (endless rotation): slip-rings
  - Option 2 (limited rotation): avoid slip-rings and use long enough cables
  - Option 3 (gear-free) : decrease the amount of mechanical components, and go for a direct-drive design!

- If this is not possible, use the presented method to improve the accuracy
- Method is simple and it works
- Method is affordable (it needs a set of accurate position sensors)
- Mechanical imperfections modeled and integrated into the control loop
- Backlash modeled and integrated into the control loop
- Positioning accuracy improved up to 5 times

⇒**from +/- 10 m to +/- 2 m at distance of 5 kilometers**

Thank you