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FINNISH GEOSPATIAL RESEARCH INSTITUTE
FGI

PAALI – Precision Agriculture ALignment Instrument

NAVISP-EL1-067

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Final Presentation

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Introduction

- ESA NAVISP-EL1 project:
  - Precision agriculture - high precision coordinate and alignments transfer
- 12 months: ~ 1.11.2023-30.10.2024

Aims / Goals

- “.. a relative high precision PNT-Attitude determination and transfer alignment system to determine each point of a mechanical ensemble ..”
- “.. define a generic model for the use of sensor fusion in the control of a mechanical ensemble, in particular machine control use cases, and then tailor it and demonstrate an extremely accurate solution for Precision Agriculture ..”
- “.. avoid the cost for an additional high end package for the each farming tool (e.g. seeder), it could be possible to determine coordinates on the seeder by a typical lever arm solution, e.g. determining the transfer attitude (transfer alignment) by an integration of visual and inertial sensors ..”

Cited from: https://navisp.esa.int/opportunity/details/89/show

⇒ Solution for articulated machinery. Estimate pose of trailed vehicle, with minimal or no components placed on the trailed vehicle.

⇒ Develop PAD (Precision Agriculture Demonstrator) prototype for testing the approach on agriculture settings

⇒ Focus on cost efficient solution, that is adaptable to a variety of similar applications/tasks.

Motivation & Background

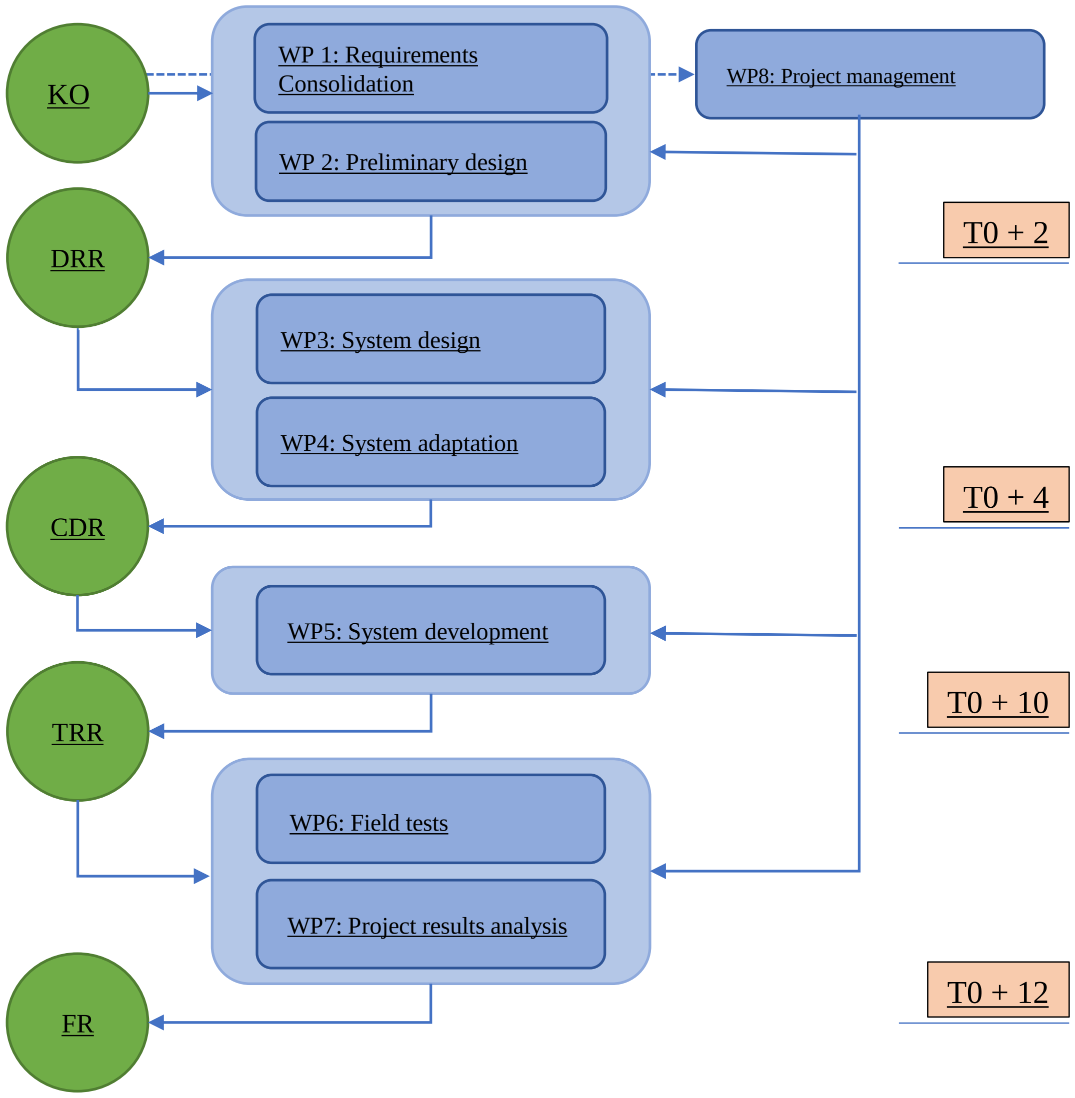
- Positioning requirements increasing
  - Agriculture looking operations at cm-level
    - Via high-performance GNSS
  - Transportation & machinery automation
    - In general, anything with articulated joints
- For multi-joint systems
  - E.g. robot fruit picking
    - GNSS becomes expensive and cumbersome
      - Joint sensoring (mechanical) is also problematic

⇒ Large potential in articulated machinery positioning
  ⇒ Needed for automation

Expected outcome

- Performance targets:
  - Aim to achieve (relative tractor-trailer)
      - position shall be better than 1cm standard deviation
        (measured from specific points between PAD and end-equipment)
      - velocity estimate between the two (due to e.g. slack in the hitch) shall be better than 5mm/s
      - heading and attitude estimation shall be better than 1 degree in any single degree of freedom
  - Cost-performance analysis
    - Algorithm, sensor recommendations
  - Real-time, low-latency prototype solution
    - Operable in benign field conditions

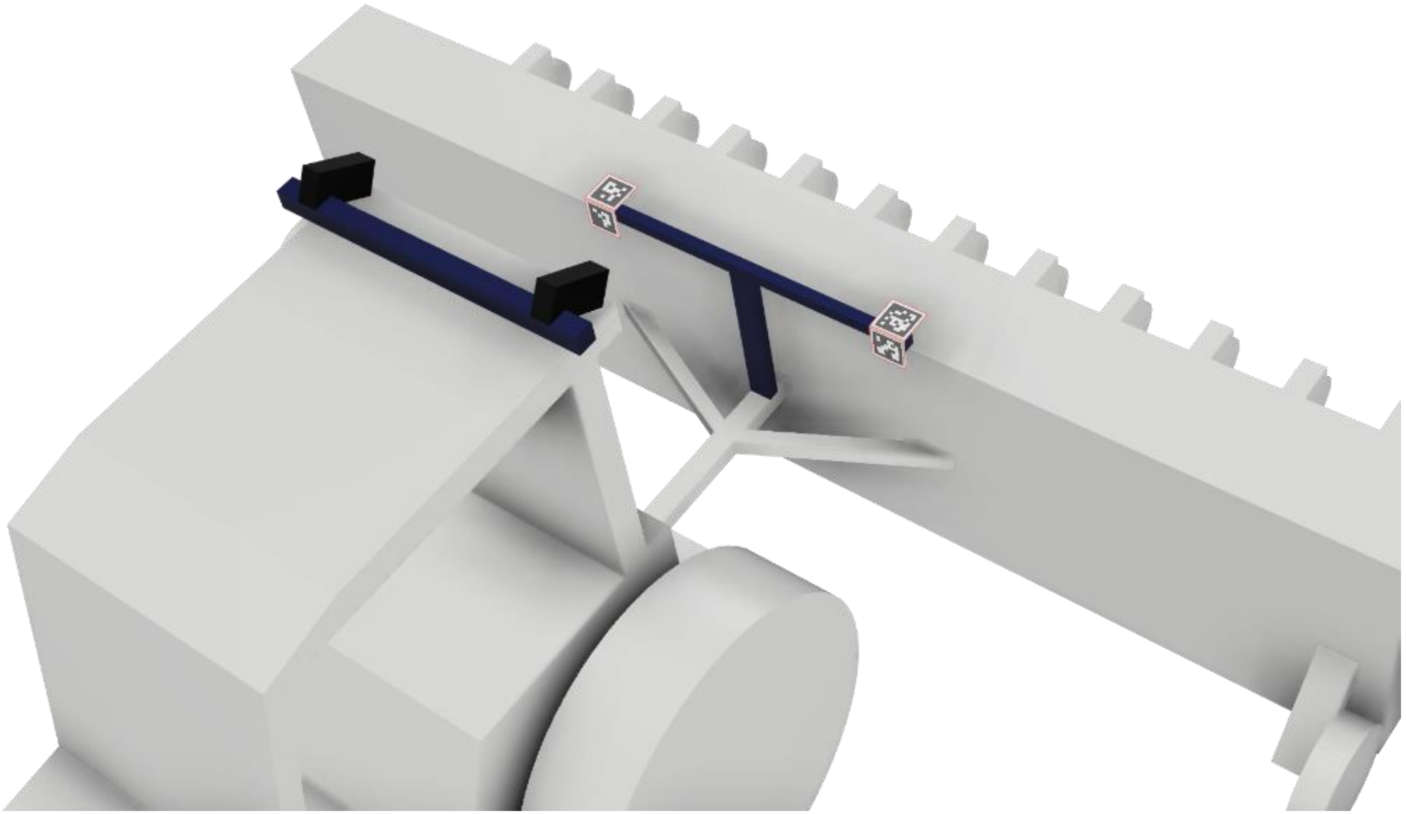
Schedule & work logic



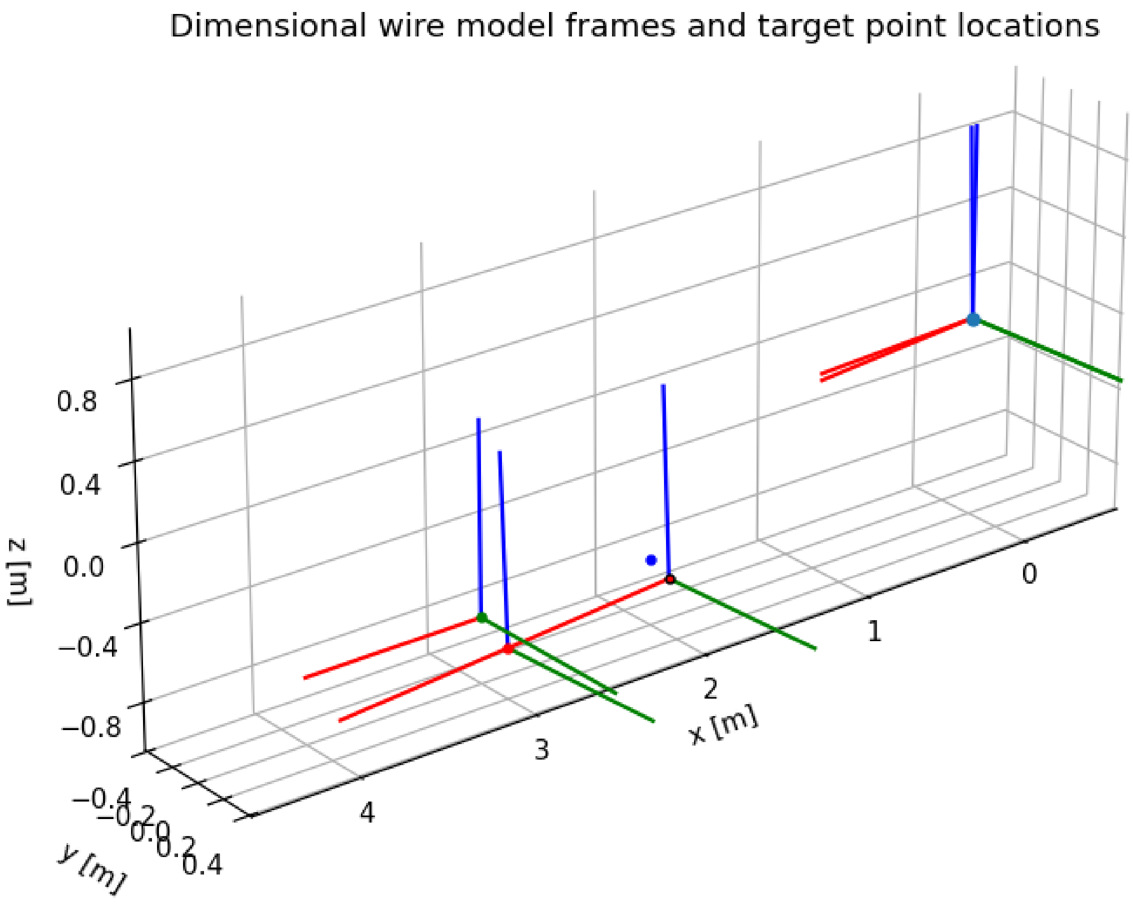
Preliminary design phase

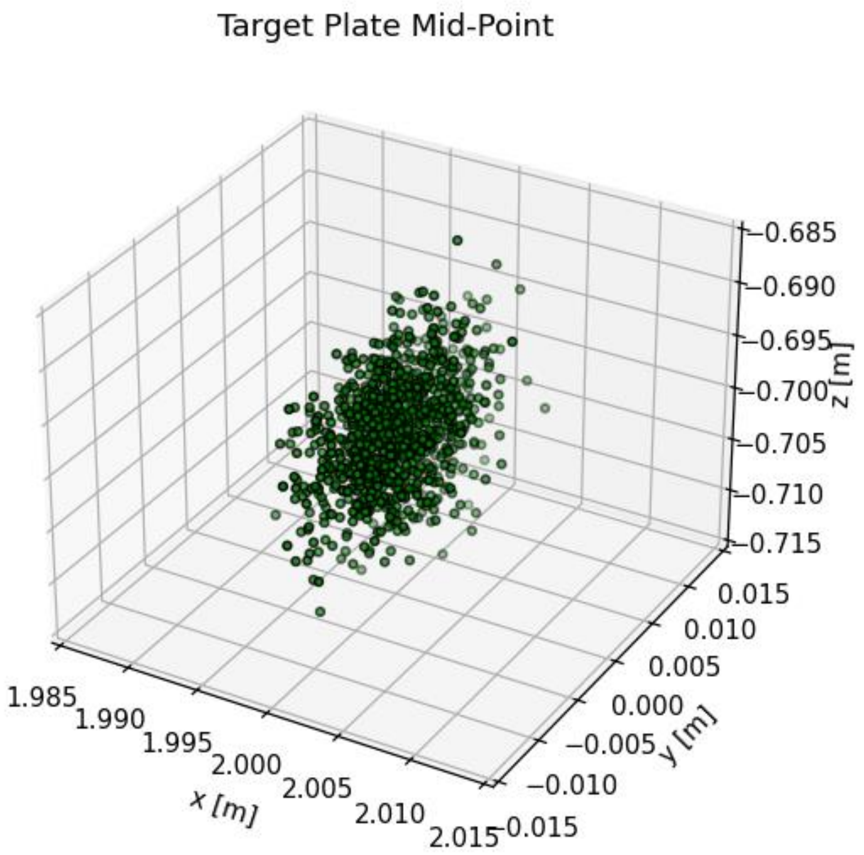
- Review of sensors and approach
  - Agricultural use case analysis
    - Conditions, requirements for robustness
    - System modeling, practical aspects
- State-of-the-art review
  - Sensors & algorithms
    - Especially vision and similar
  - System models for joint kinematics
  - Sensor fusion
- Simulation for accuracy analysis

Preliminary concept



Simulations, accuracy requirements





Preliminary design phase conclusions

- Focus on camera and machine vision solutions
  - Cost-performance reasons
    - RF-solutions could replace or augment in the future?
- Sensor fusion and modeling a challenge
  - Large nonlinearities and discontinuities, e.g. hitch
    - Agricultural equipment may need operational adjustment of parameters
  - Three approaches identified:
    - Direct measurement without kinematic or non-holonomic constraints
    - Kinematic model of a tractor-trailer joint dynamics with hard-coded parameters and dimensions
    - Kinematic model with some (or all) of the parameters estimated online by the sensor fusion

$\Rightarrow$ From business perspective, the ‘direct measurement’ most attractive and modular

$\Rightarrow$ No need to develop tool specific models.

$\Rightarrow$ Parameter estimation likely unstable, not fast enough and still require some underlying model structure.

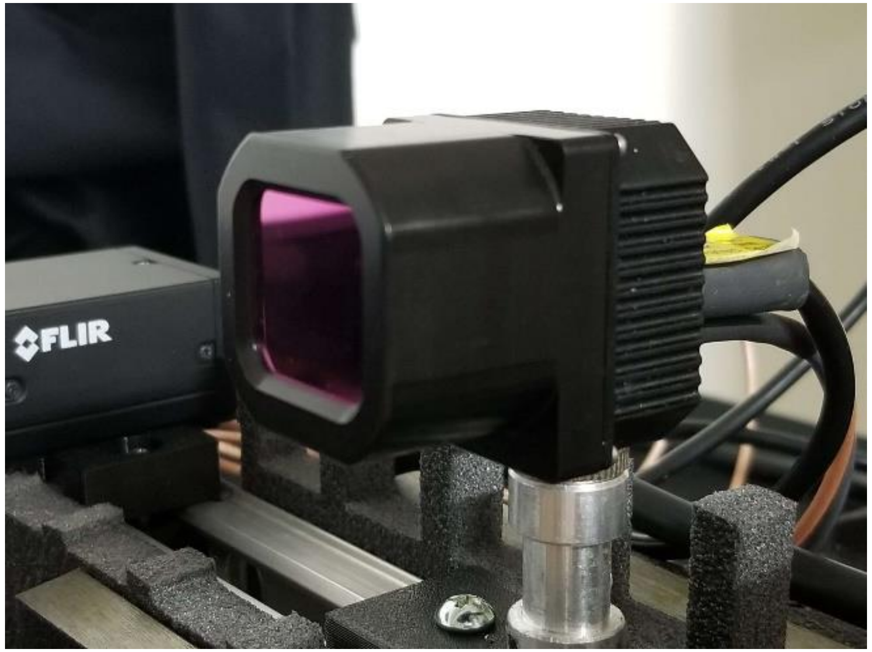
Design phase

Preliminary testing of (existing) sensors:

- Rough assessment of robustness, accuracy
  - Stereocamera, Time-of-flight camera, thermal camera, lidar
- Evaluation of SLAM against dust conditions using publicly available material

Design phase

- Variety of (artificial) robustness tests
  - Accuracy againts degradation in visual conditions



Design phase

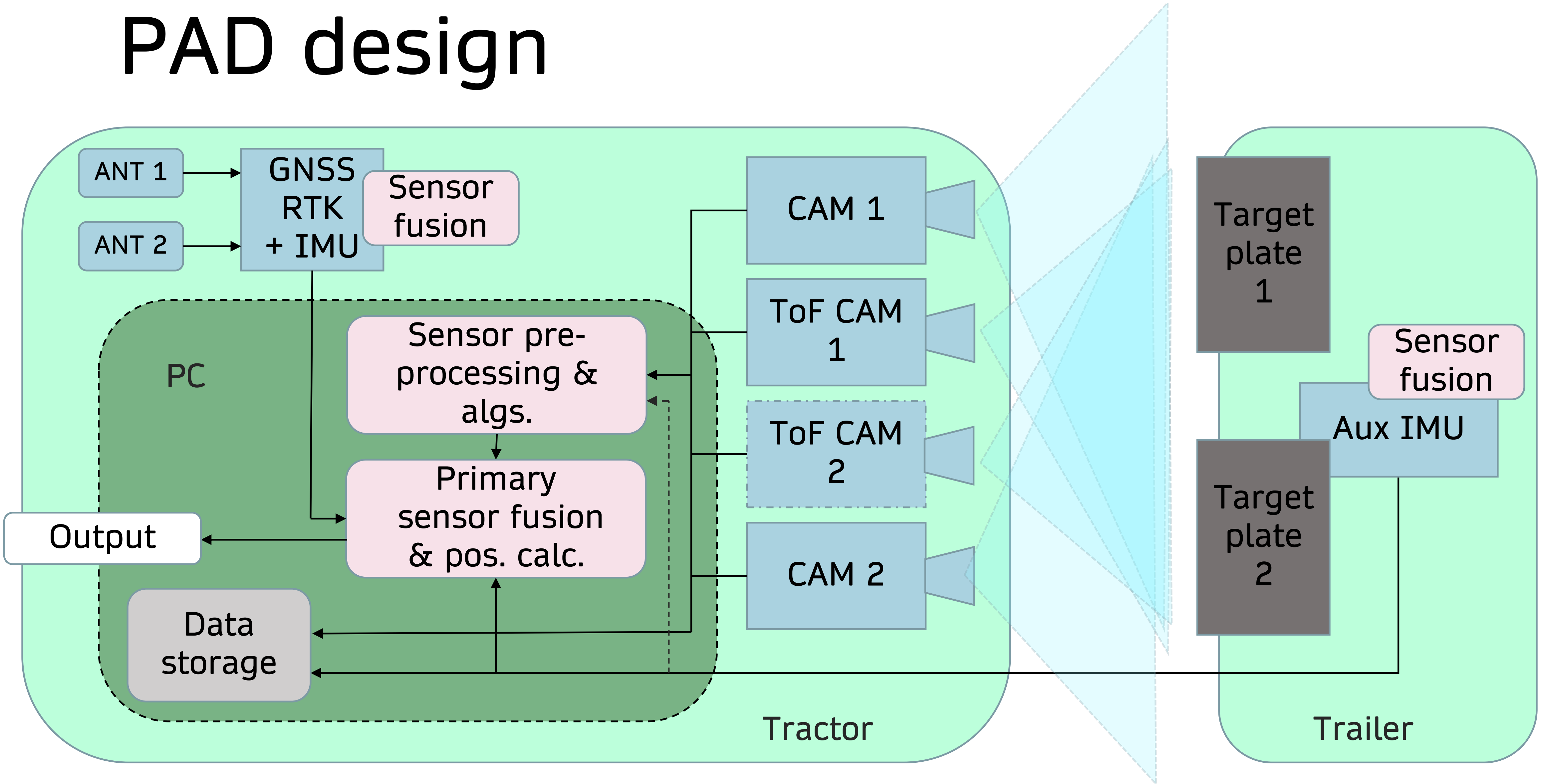
- Early testing of algorithms
  - Literature review gave remarkably few indications on the accuracy of typical algorithms

    ⇒ Need for testing

Design choices

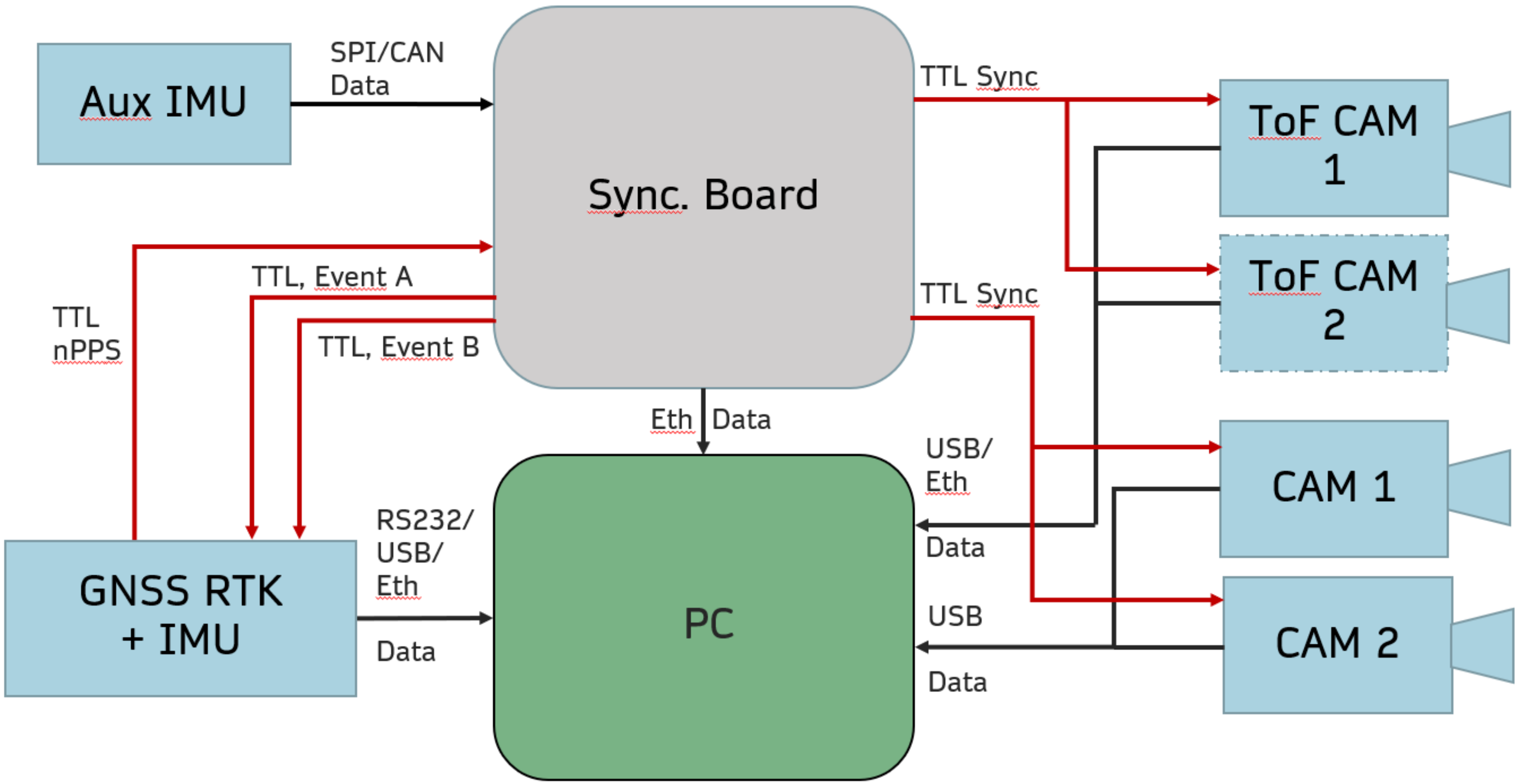
- Absolute positioning for the tractor:
  - GNSS dual-antenna, with IMU
    - No real alternatives
- Focus on stereocamera and ToF-camera
  - Relative positioning between tractor-trailer with optical markers
- Use ‘direct’ measurement with minimal or no kinematic model
  - Sensor fusion for evaluation and if needed
- Preferably no components on the trailer
  - But auxiliary IMU was seen feasible in commercial solution (ISOBUS)
- Use of Robot Operating System as a framework

PAD design


ANT 1
ANT 2
GNSS RTK + IMU
Sensor fusion
CAM 1
ToF CAM 1
ToF CAM 2
CAM 2
PC
Sensor pre-processing & algs.
Primary sensor fusion & pos. calc.
Output
Data storage
Tractor
Target plate 1
Sensor fusion
Aux IMU
Target plate 2
Trailer

Synchronization and data flow

- Plan for very tight sensor synchronization
  - For COTS, IO-bus/IF often problematic, e.g USB
  - ROS/Linux timestamping



Test plan

Validation

- Unit (component) tests
- Subsystem tests
- Integration tests
- Preliminary trials
  - Car-trailer
  - Tractor-seeder

Acceptance / Qualification

- Final field trials
  - Tractor-seeder with full PAD functionality
  - Benign conditions in agriculture settings
  - Reference system

Reference solution

Choices:

- Photogrammetry
- Laser trackers, total stations
- GNSS-IMU units
- RF-systems (non-GNSS/local)
- Manual markings

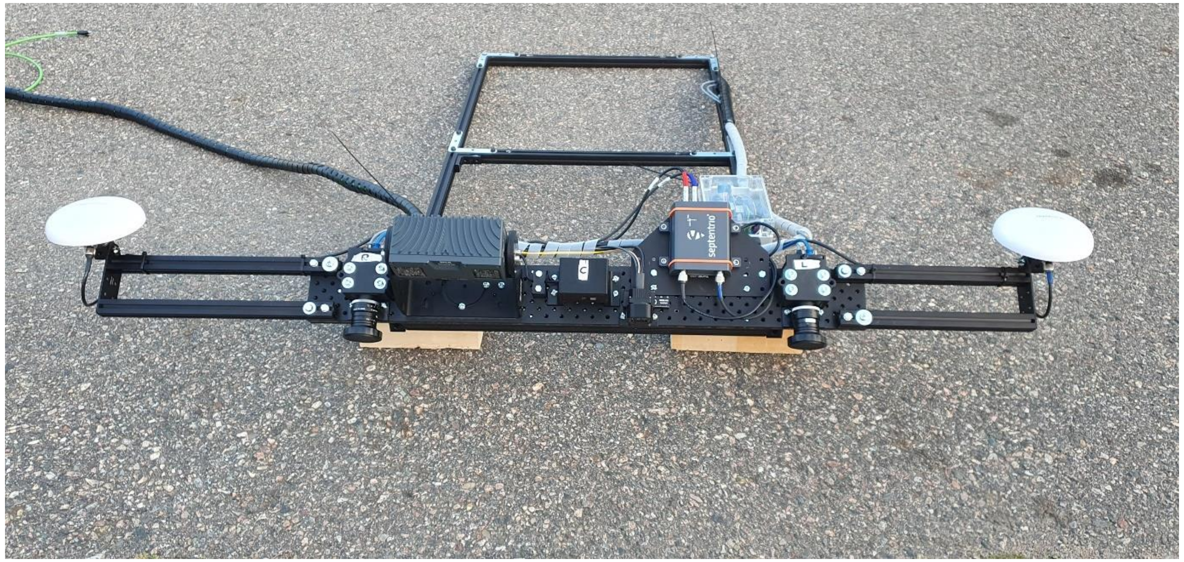
Challenges:

- Optical methods difficult for continuous, 360 degree measurement
  - Require prisms/tags
    - Error small for shorter ranges
      - Need for pseudostatic runs
- GNSS-IMU position accuracy poor for evaluation, GNSS update rate low
- RF-system accuracies very low

$\Rightarrow$ Plan to utilize tactical grade RTK-GNSS-IMU unit and another dual-antenna RTK-GNSS-IMU unit

Development phase
PAD build-up

- PAD prototype built and tested in several phases (final version shown)
- Main tractor side components:
  - Septentrio SBi3 Pro+
    - Dual antenna + IMU
  - 2x Flir Grasshopper monochrome camera
  - Sick Visionary B stereocamera
  - Analog devices ToF-camera evaluation kit
  - Flir thermal camera
  - Semi custom synchronization board
  - Desktop PC + Anker powerbank (not shown)



Development phase PAD build-up

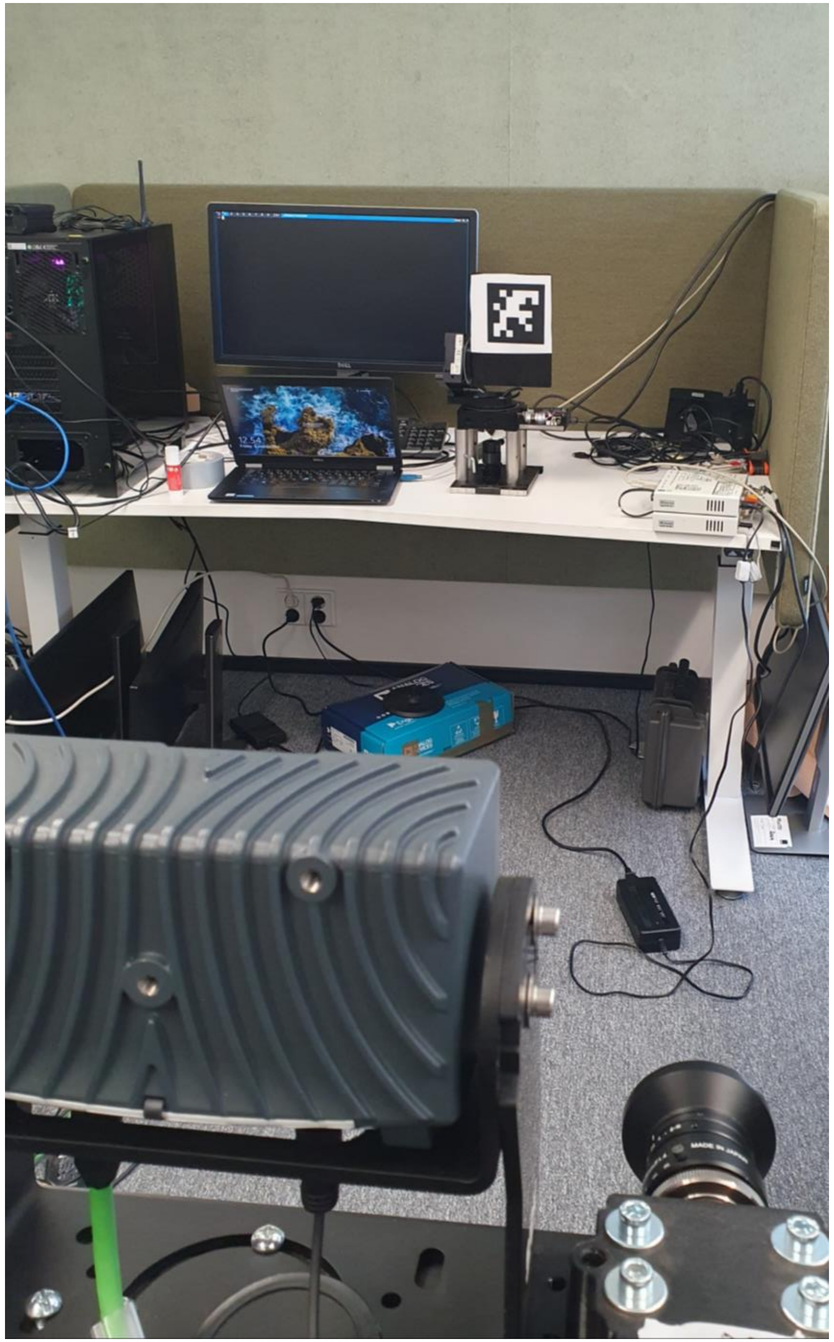
- PAD prototype seeder side (version during preliminary trials)
- Main components:
  - Two sets of dual markers
  - Auxiliary IMU interfaced via miniature PC
  - Two reference systems:
    - Tactical grade RTK-GNSS with high quality IMU
    - Dual antenna RTK-GNSS-IMU unit
      - Identical to the PAD allowing direct comparison
    - One antenna shared via splitter between the two GNSS units
  - Battery bank and power distribution components

Development phase Software design

- Robot Operating System (ROS2) as a framework
    - Drivers for all sensors / components
    - Functionality for record & replay, visualization, data handling
        - SW timestamping of data
        - Coordinate/pose transformations
- Computer vision based on OpenCV

Development phase
Sensor testing

- Environmental tests
- Algorithm tests
  - Accuracy / precision tests
    - Pose (position / attitude)
  - GNSS-IMU lever arm
- Timing, jitter & latency
- Calibration tests
- Data record & replay tests



Development phase
Sensor testing

Impact of outdoor conditions:

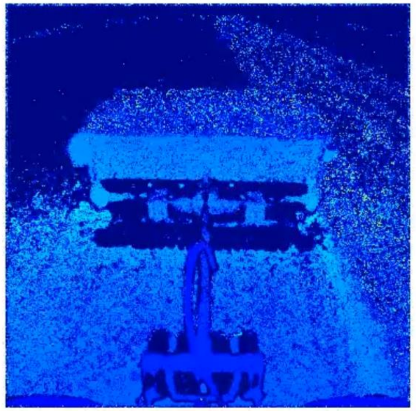
Stereo pair: left

Stereo pair: right

Thermal

ToF image

ToF radial depth



Development phase
Sensor testing

Impact of outdoor conditions:

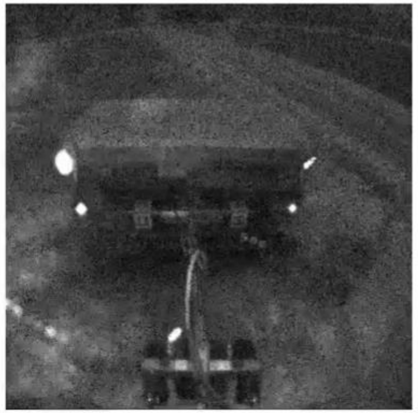
- ToF problematic
  - Susceptible to ambient light, dust etc
- Thermal camera not beneficial unless poor lighting conditions

Stereo pair: left

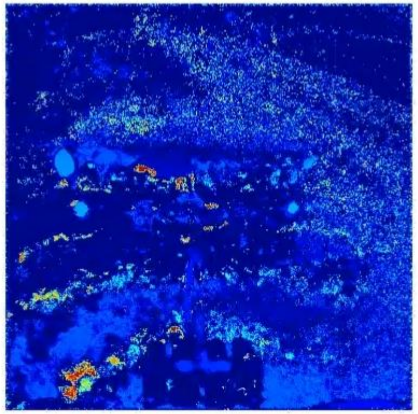
Stereo pair: right

Thermal

ToF image



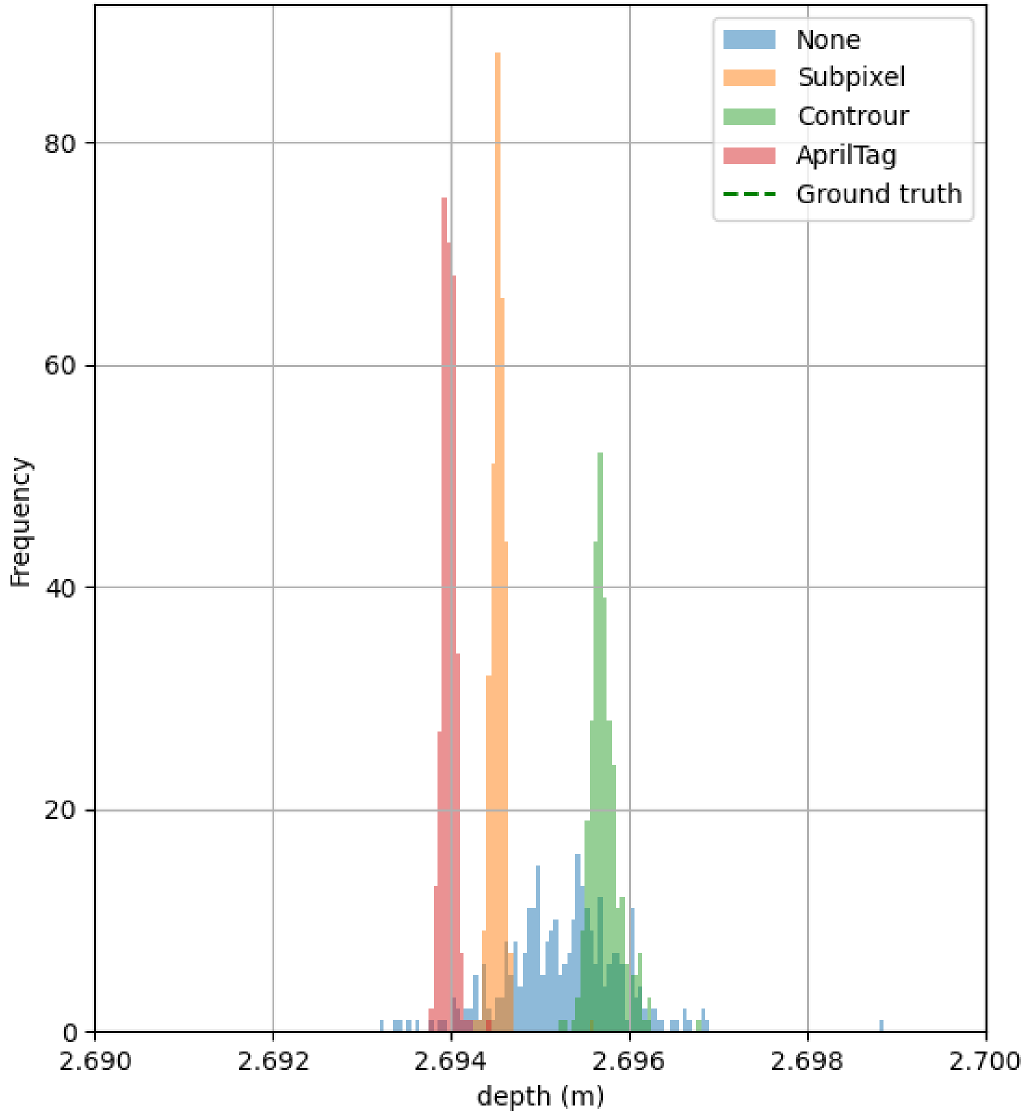
ToF radial depth



Development phase Algorithms

Marker detection:

- None, meaning there is no subpixel refinement
- Subpixel refinement
- Contour-based refinement
- Aruco-based refinement.

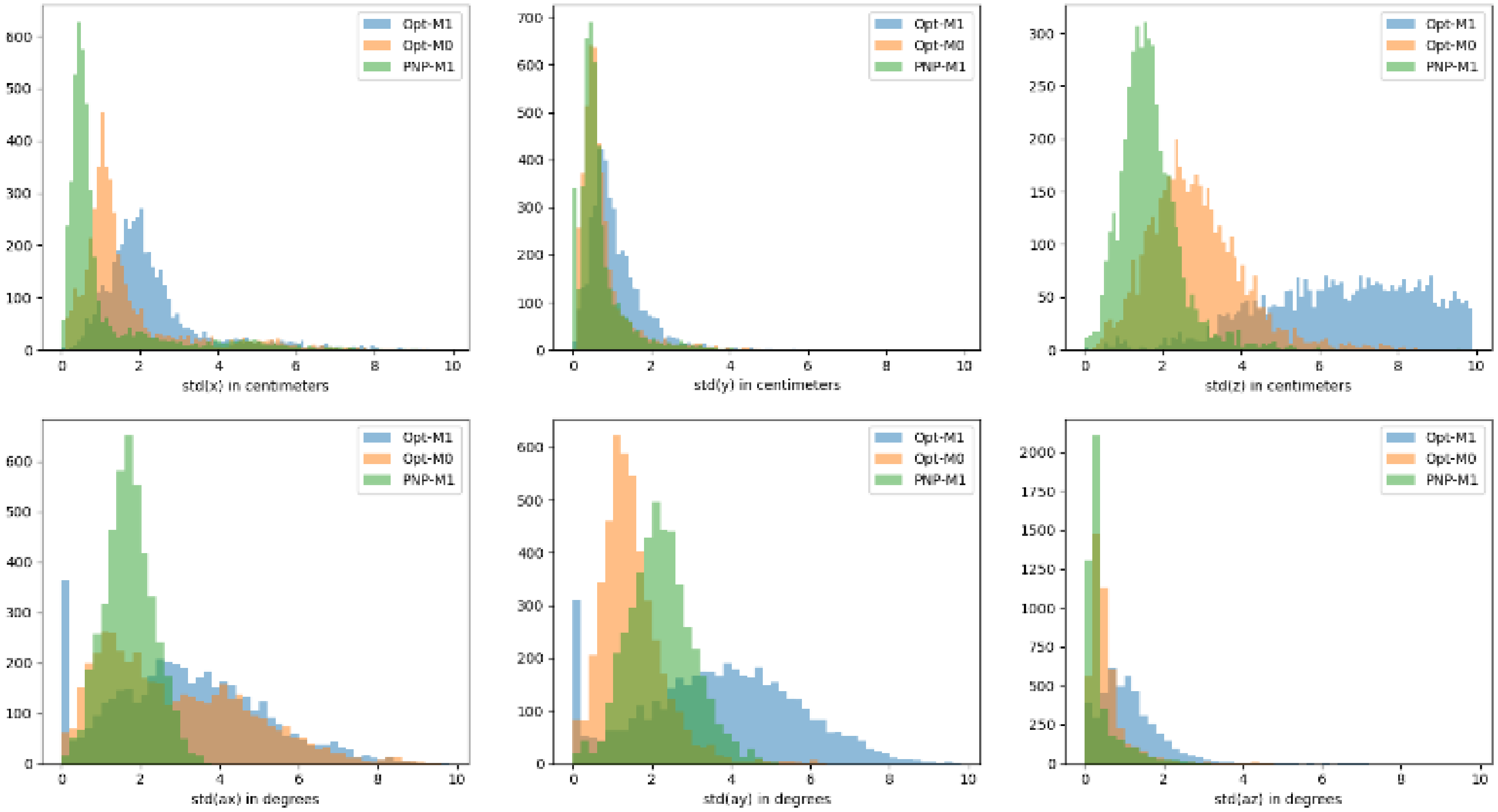


- Ground truth is 2.665 m

Development phase
Algorithms

Stereo camera algorithms:

- Opt-M0 and Opt-M1 refer to different variants of optimization based algorithm
- PnP (Perspective-n-Point) refers to Levenberg-Marquardt based PnP-algorithm



Development phase Calibrations

Sensor pose and timing:

- GNSS-IMU
- Camera-camera
- Camera-IMU
- Baselines
- Reference systems

⇒ Algorithms, but also manual measurements

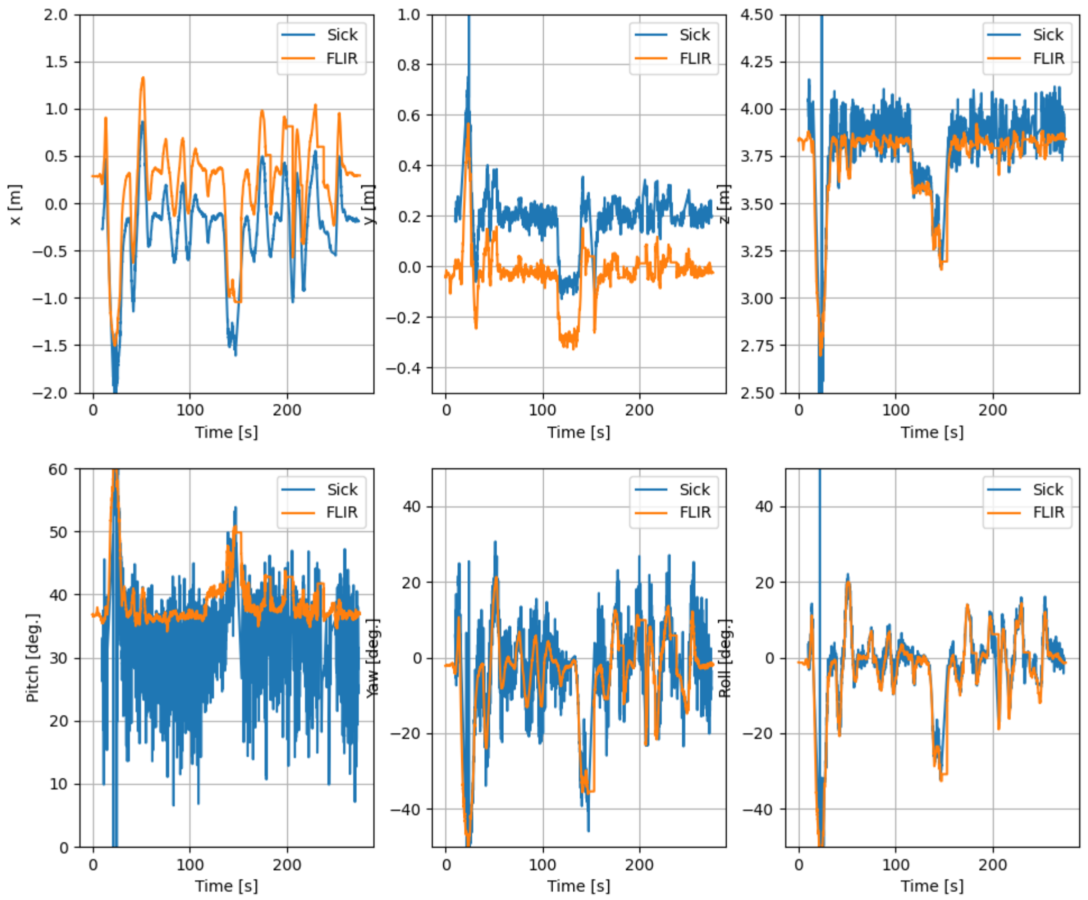
Development phase
Sensor evaluations

Evaluation of machine vision pose estimation precision:

- ToF vs Std. camera
- Stereo camera resolution comparison

General operating parameters

- Frame-rate tests
- Illumination / shutter



Development phase testing

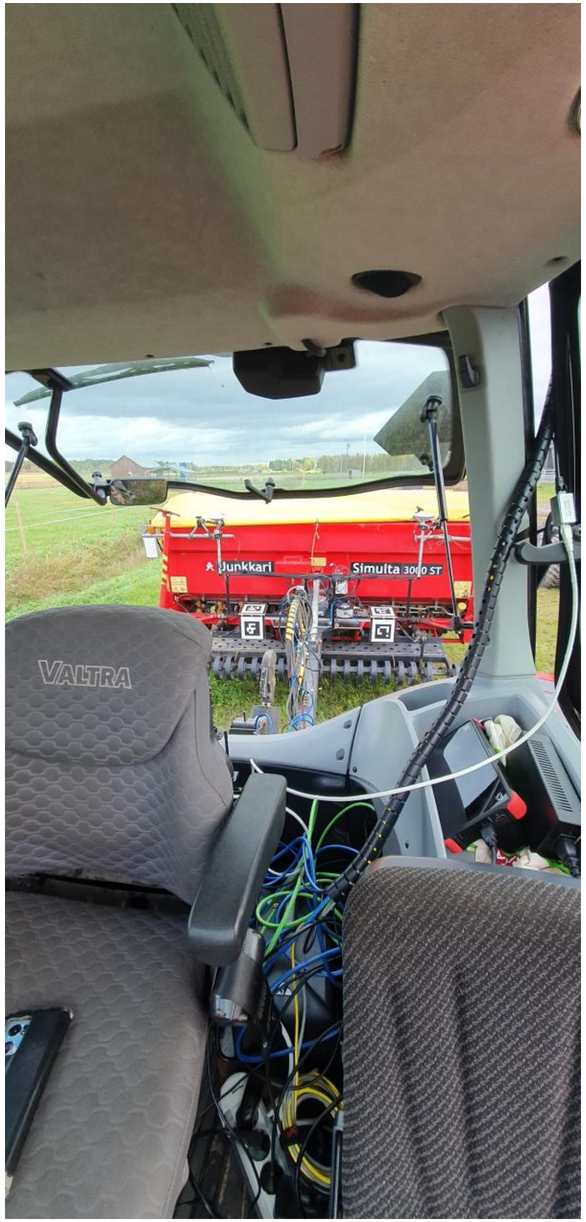
Laboratory tests mainly pass with few tests canceled

Field testing:

- Earlier than expected opportunity to test with tractor
  - Mainly for environmental testing
- Two sets of car-trailer tests
  - Largely for functional testing
- Preliminary field trial with tractor-seeder
  - Full functionality
    - Some minor improvements for final field trials

Test ID	Title	Status
CT1	Std camera	Pass
CT2	ToF camera	Pass
CT3	GNSS–IMU system	Pass
CT4	Auxiliary IMU	Pass
CT5	Synchronization board	Pass
CT6	PC/ROS	Pass
ST1	Std camera sync	Pass
ST2	ToF camera sync	Canceled
ST3	ToF light interference	Pass
ST4	GNSS–IMU system	Fail
IT1	Synchronization	Partial pass
IT2	Calibration tests	Pass
IT3	Camera distance accuracy	Pass
IT4	Camera target attitude estimation accuracy	Pass
IT5	Error characterization	Pass
IT6	PC recording and processing	Pass
IT7	Dynamic accuracy	Partial pass
IT8	Sensor fusion	Canceled
PT1	Car–trailer test 1	Pass
PT2	Car–trailer test 2	Partial
PT3	Preliminary field test on tractor	Pass
FFT1	Final field trial	Done, QT1-QT5 analysis in STRv1

Field trial preparations

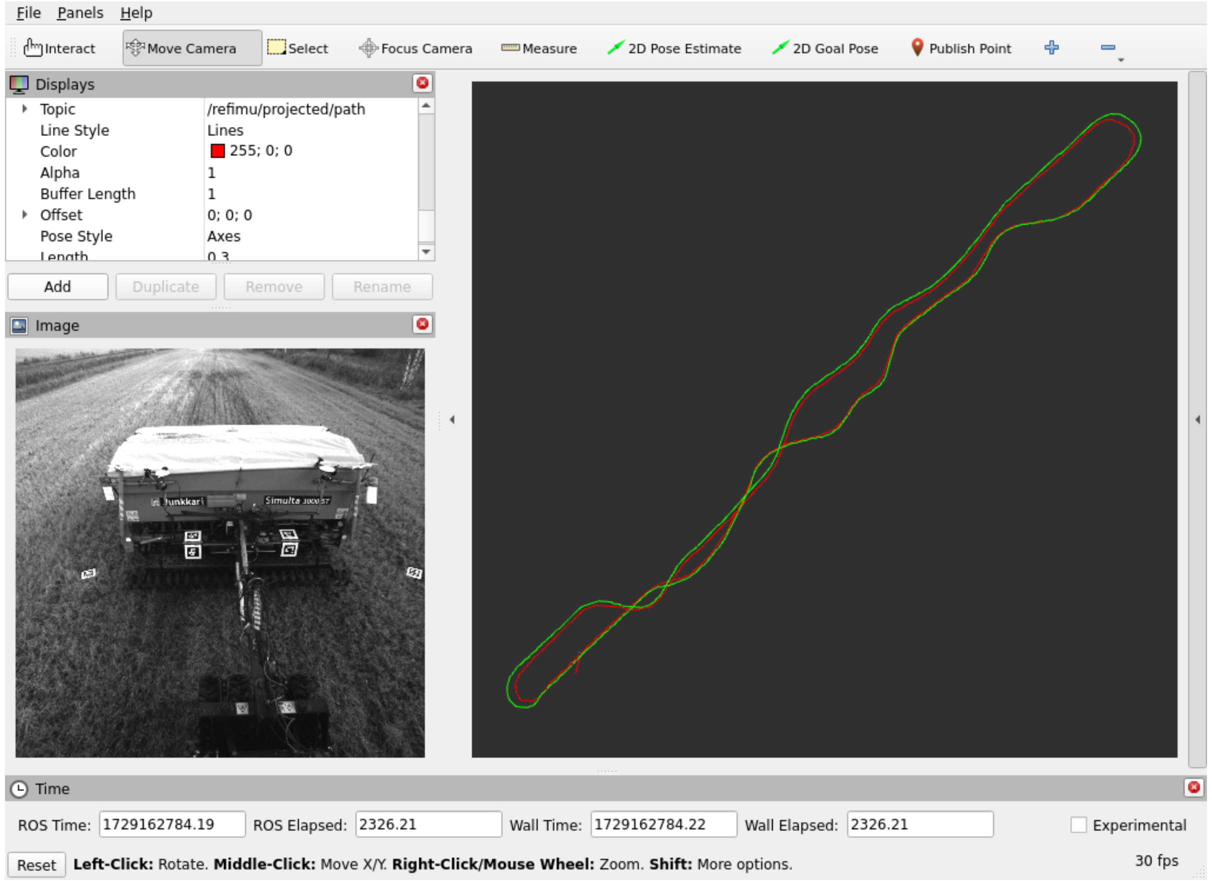


Field trial preparations

Preliminary field trials (video)

Final field trials (video)

Field trial results (video)



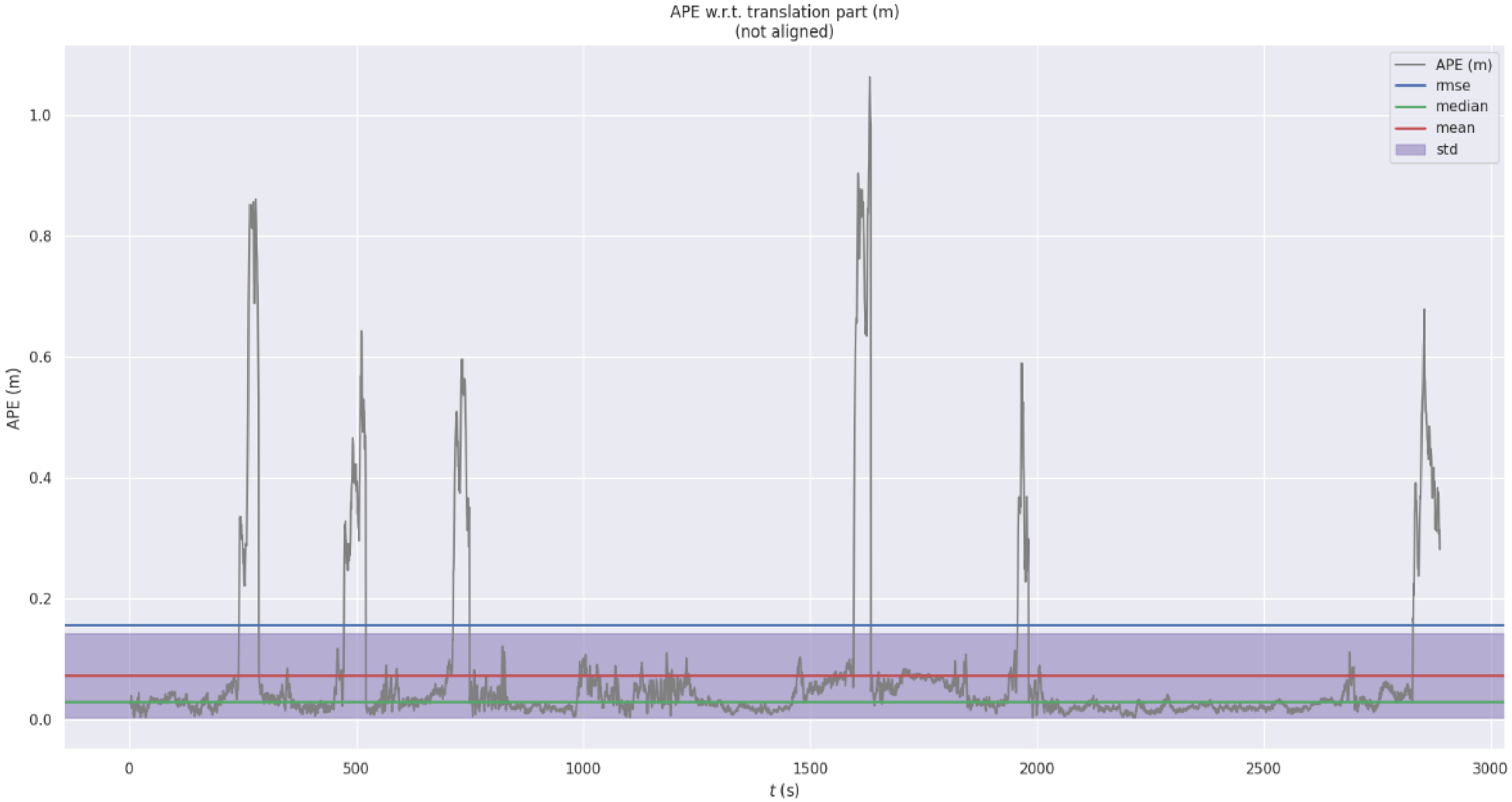
Field trial results

Absolute position error between end-equipment references.

- Spikes indicate loss of RTK

FINPOS base station ~30km away

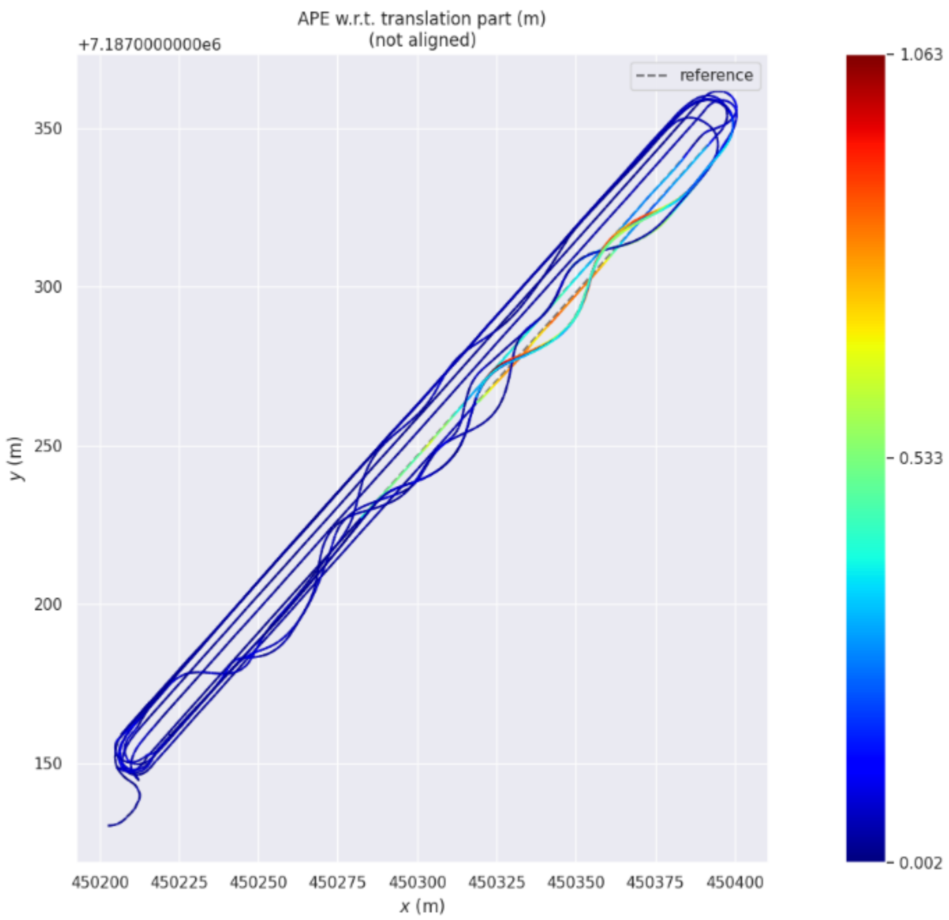
- RTK real-time corrections not perfect

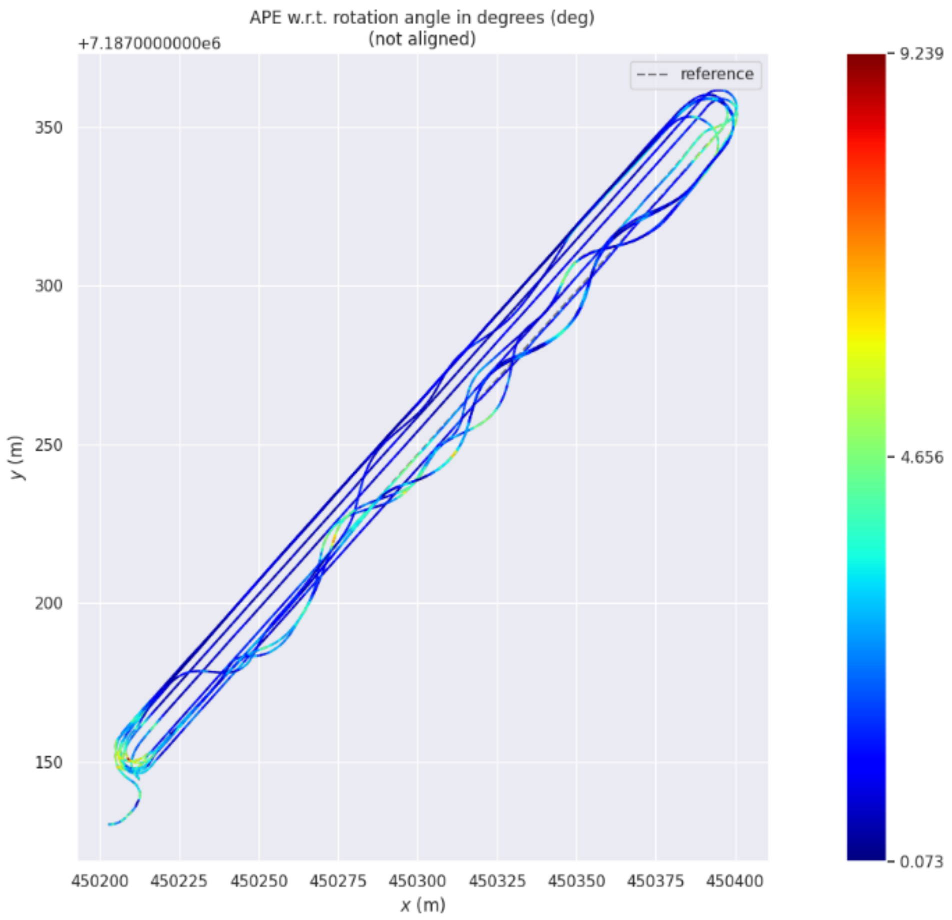


Field trial results

Absolute pose error between the reference GNSS systems:

- Left: position
- Right: orientation

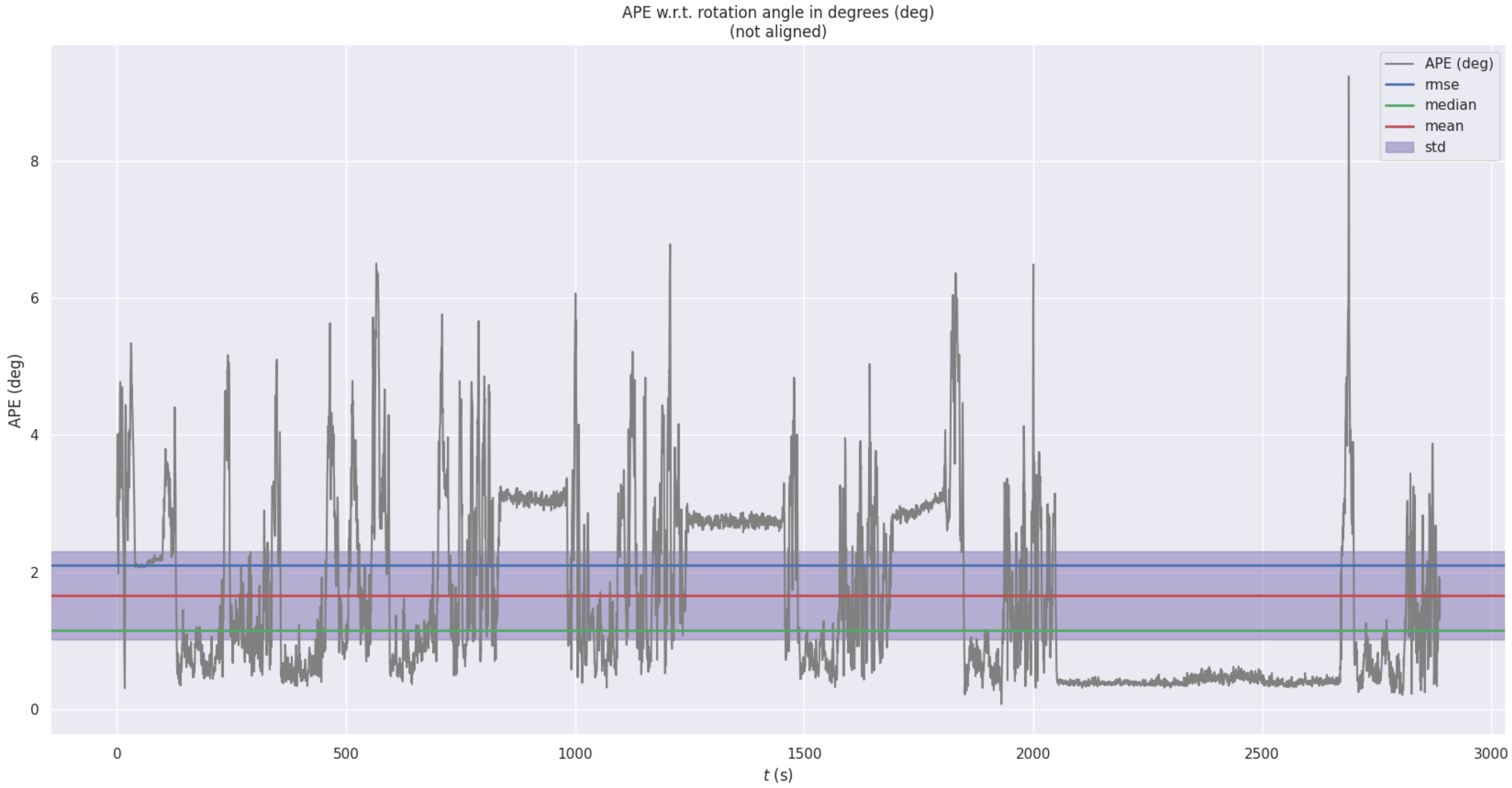




Field trial results

Reference Septentrio full orientation error

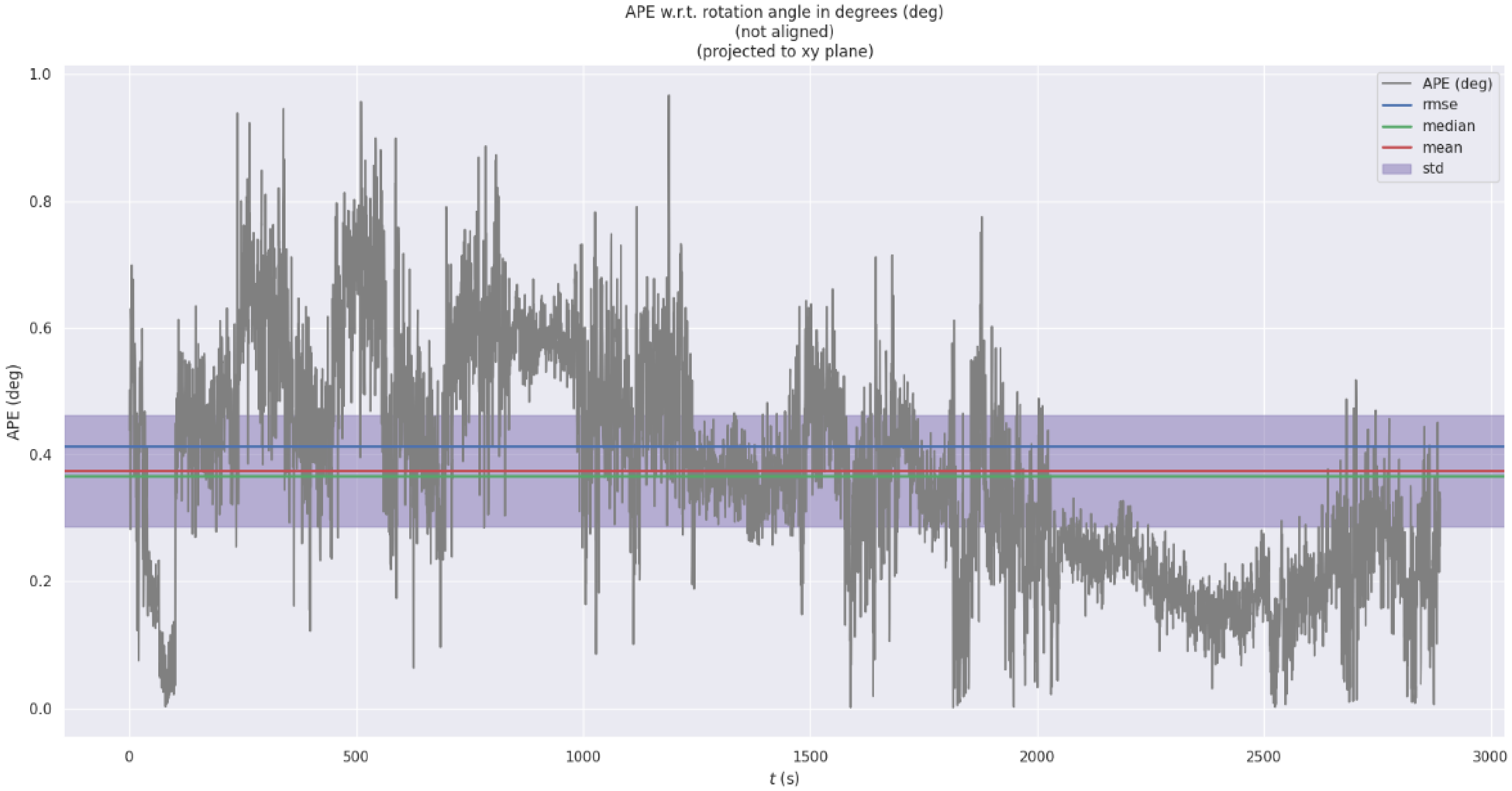
- Median 1.15°
- Occasionally reaches >9°



Field trial results

Reference Septentrio 2D orientation error (heading)

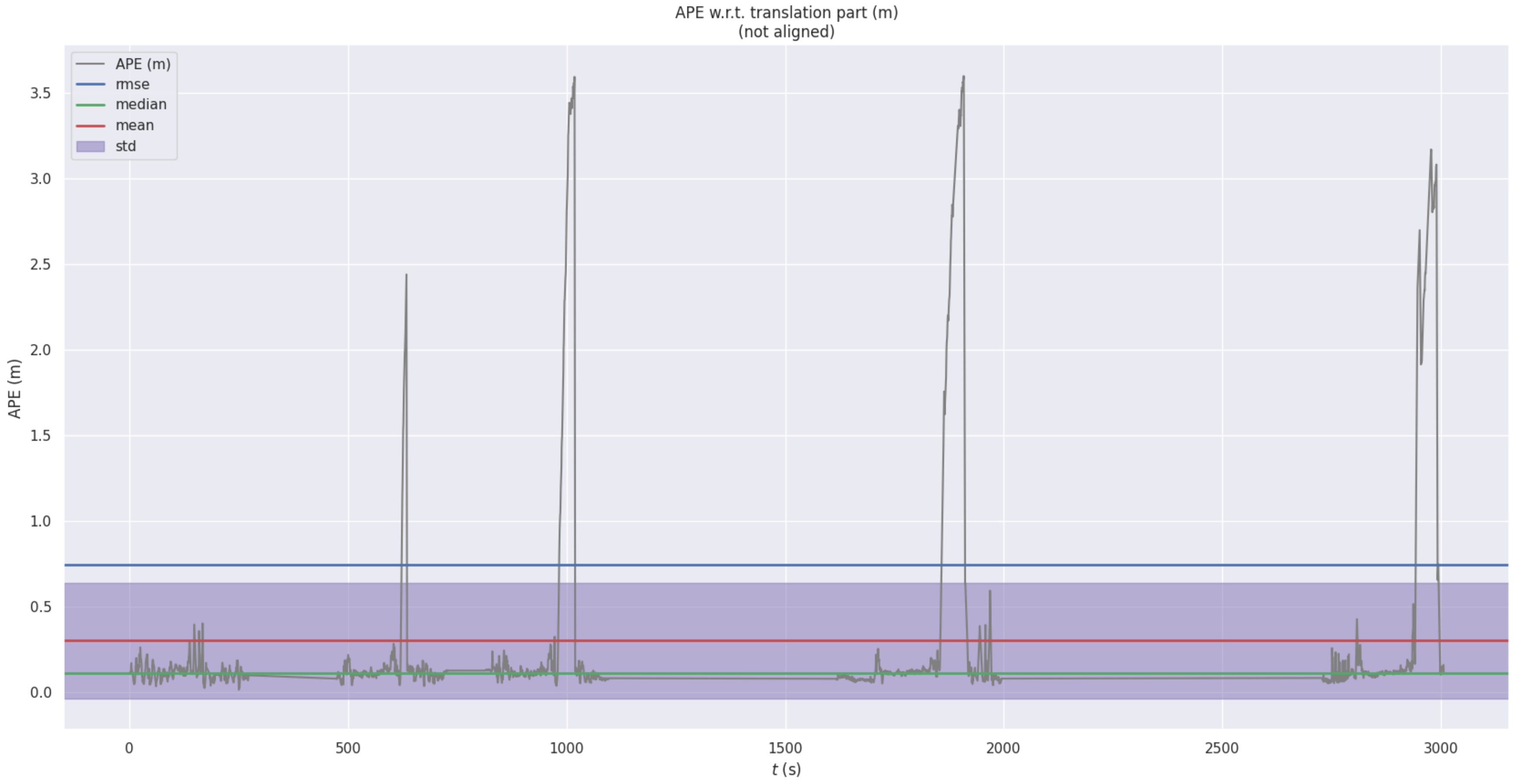
- Median 0.37°



Field trial results

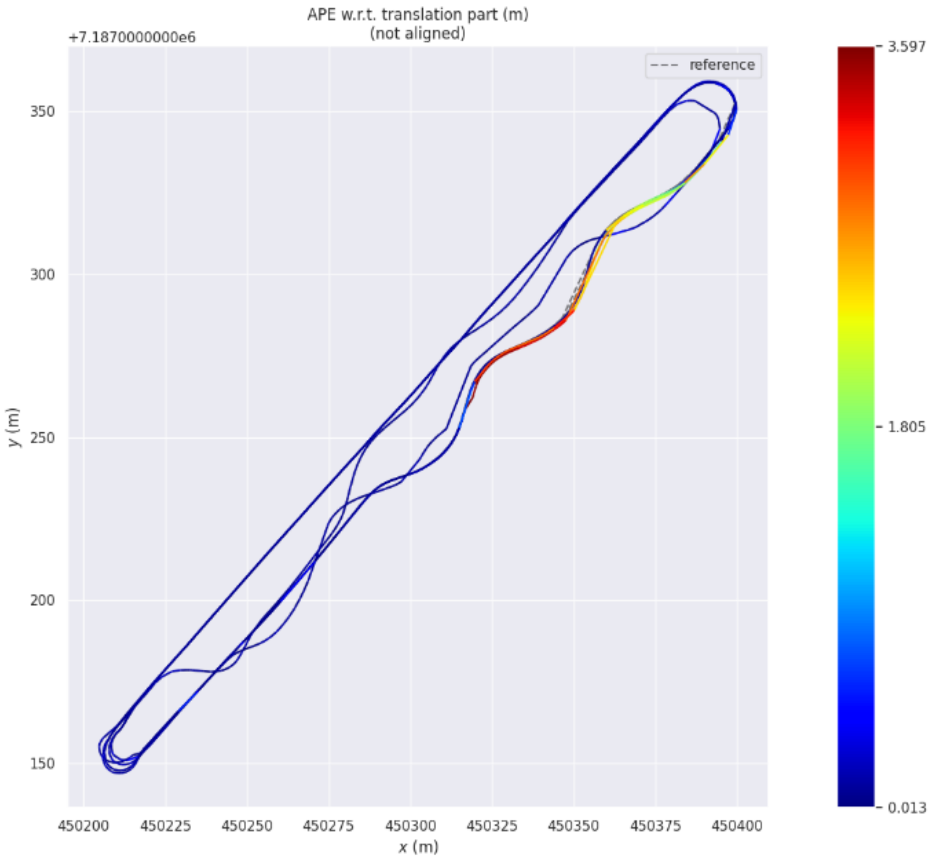
PAD absolute position error

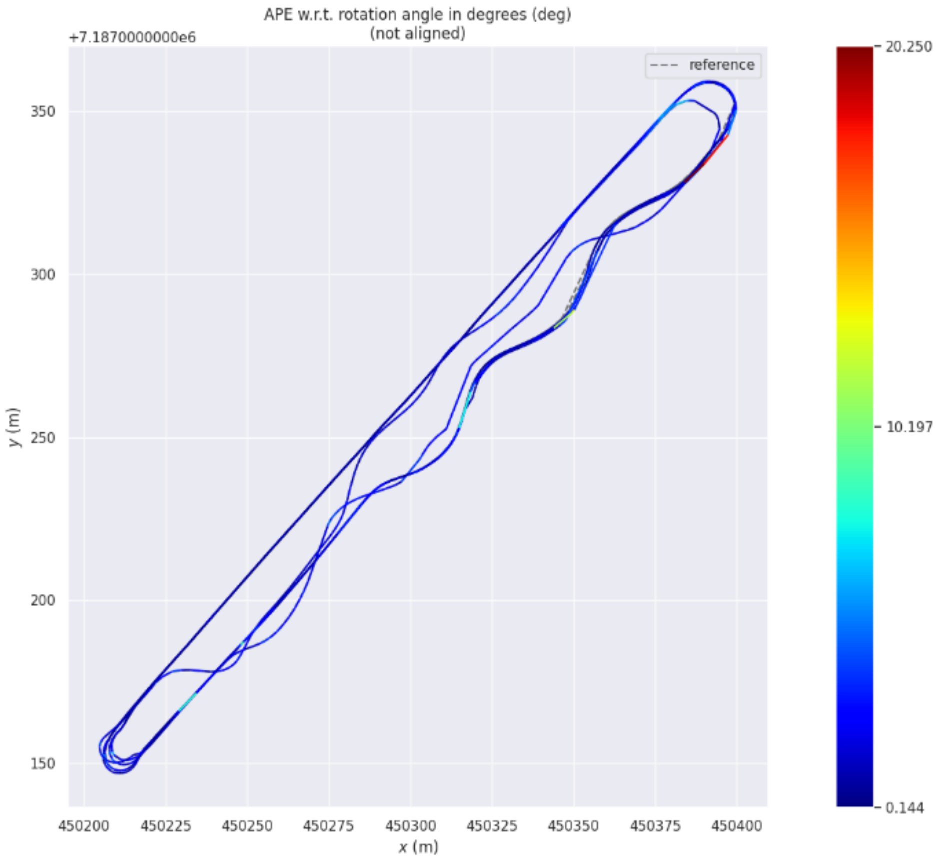
- Median 11cm
- RTK cause for large spikes
- Camera vision issues cause for smaller spikes



Field trial results

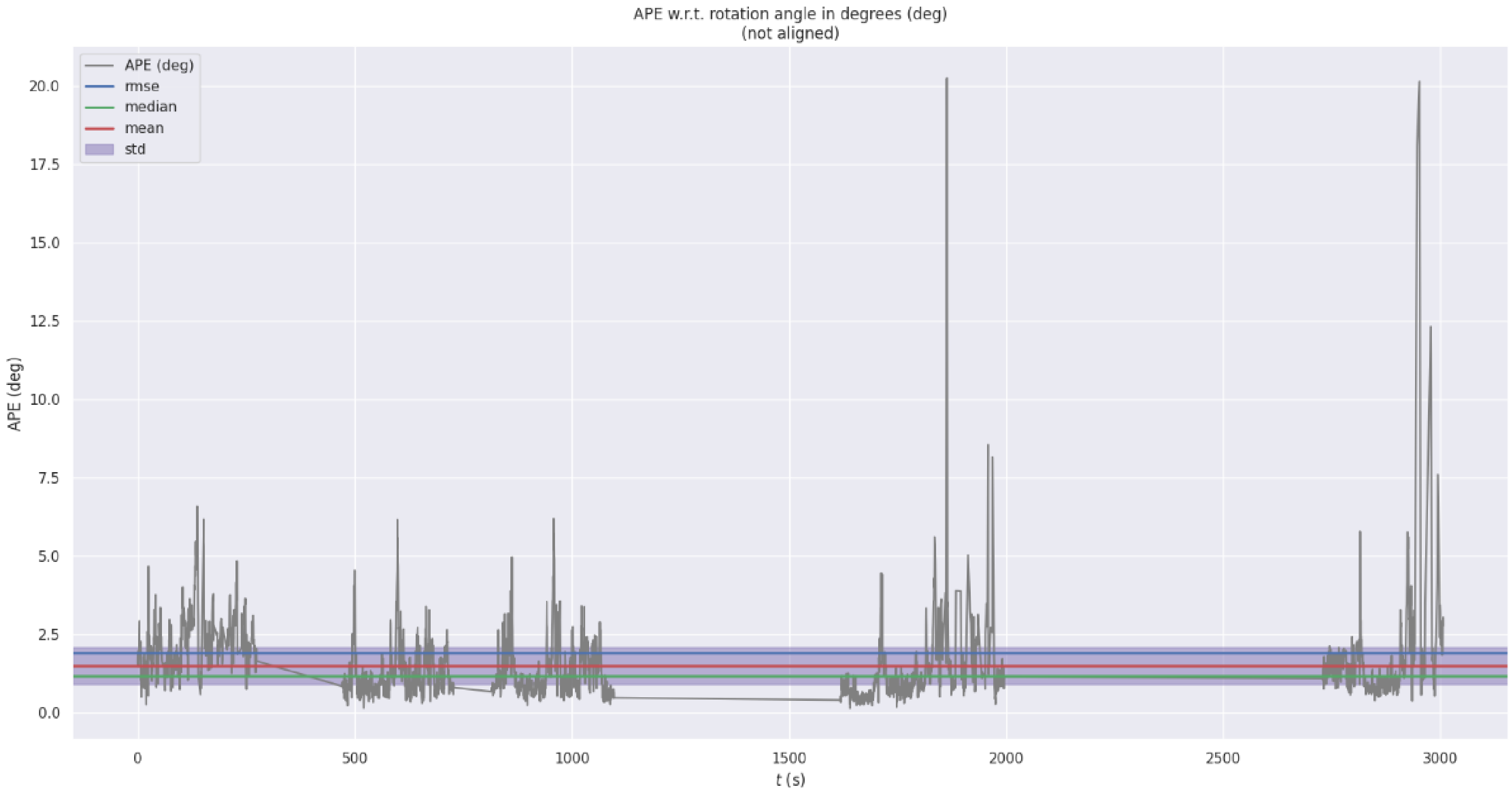
Absolute pose error of the PAD solution





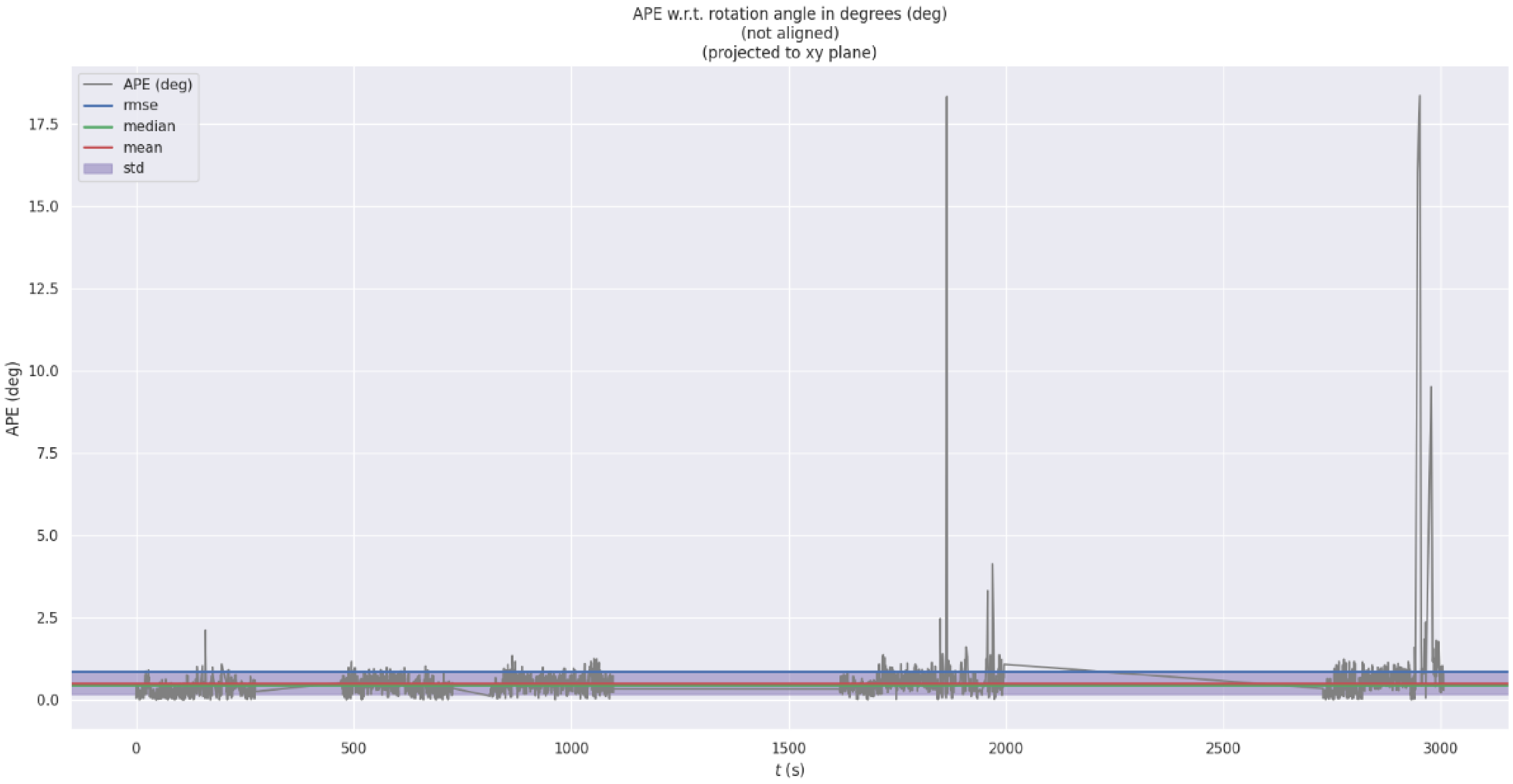
Field trial results

Full orientation of the PAD solution



Field trial results

2D orientation of the PAD solution



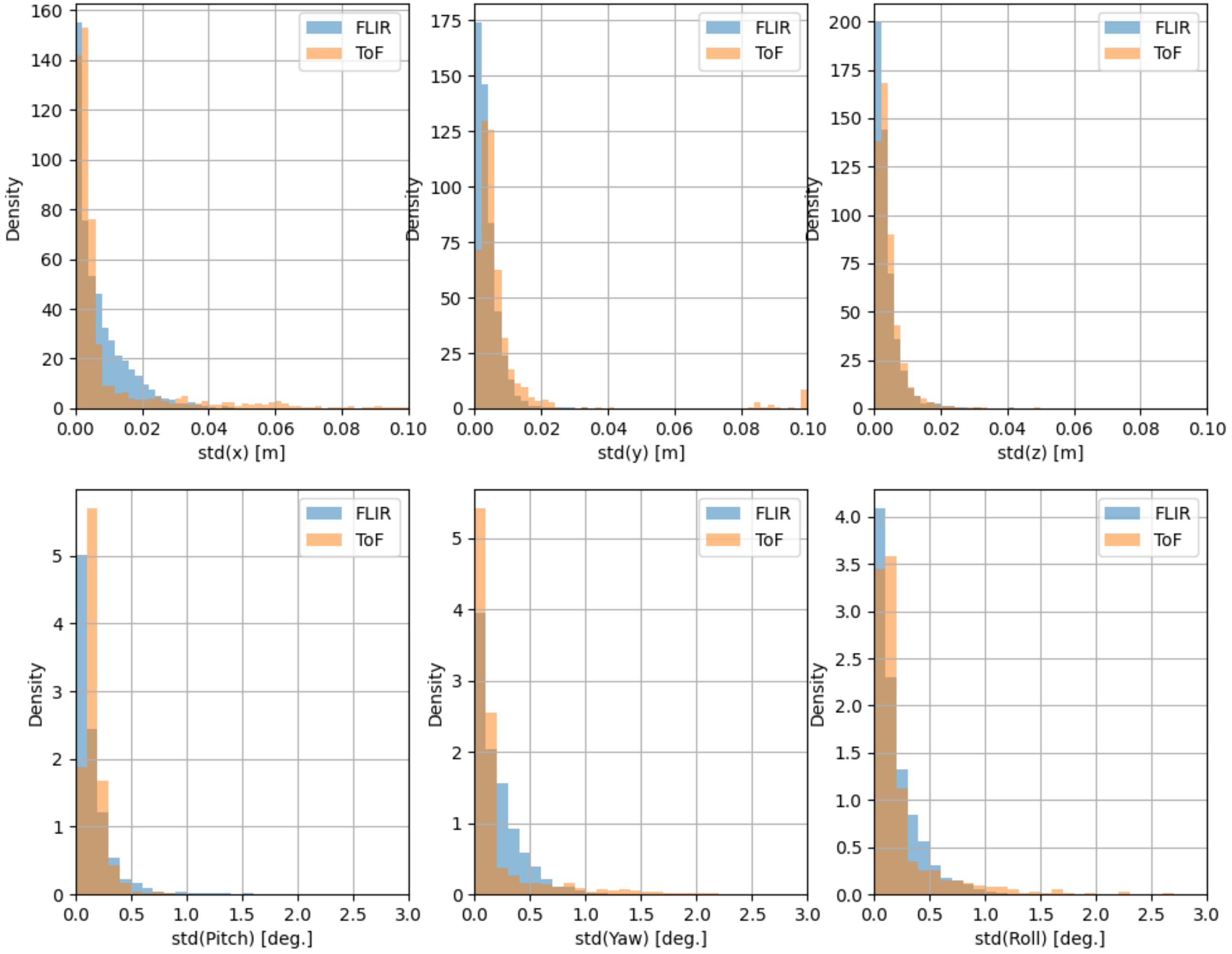
Field trial results

System/metric	Position error median (cm)	Position error mean (cm)	Orientation error median (deg)	Orientation error mean (deg)	Heading error median (deg)	Heading error mean (deg)
GNSS Ref.	3.0	7.25	1.15	1.66	0.367	0.375
Direct meas. system	11.0	29.90	1.18	1.51	0.44	0.50

- Absolute orientation errors of the PAD appear to be very good and almost on par with equivalent end-equipment mounted RTK-GNSS-IMU unit
- Absolute position error is larger than expected
  - Septentrio RTK-GNSS-IMU unit appears to suffer from poor RTK corrections
    - 1° error in tractor orientation estimate yields 7-8cm absolute position error for the PAD at marker distance of 4m.

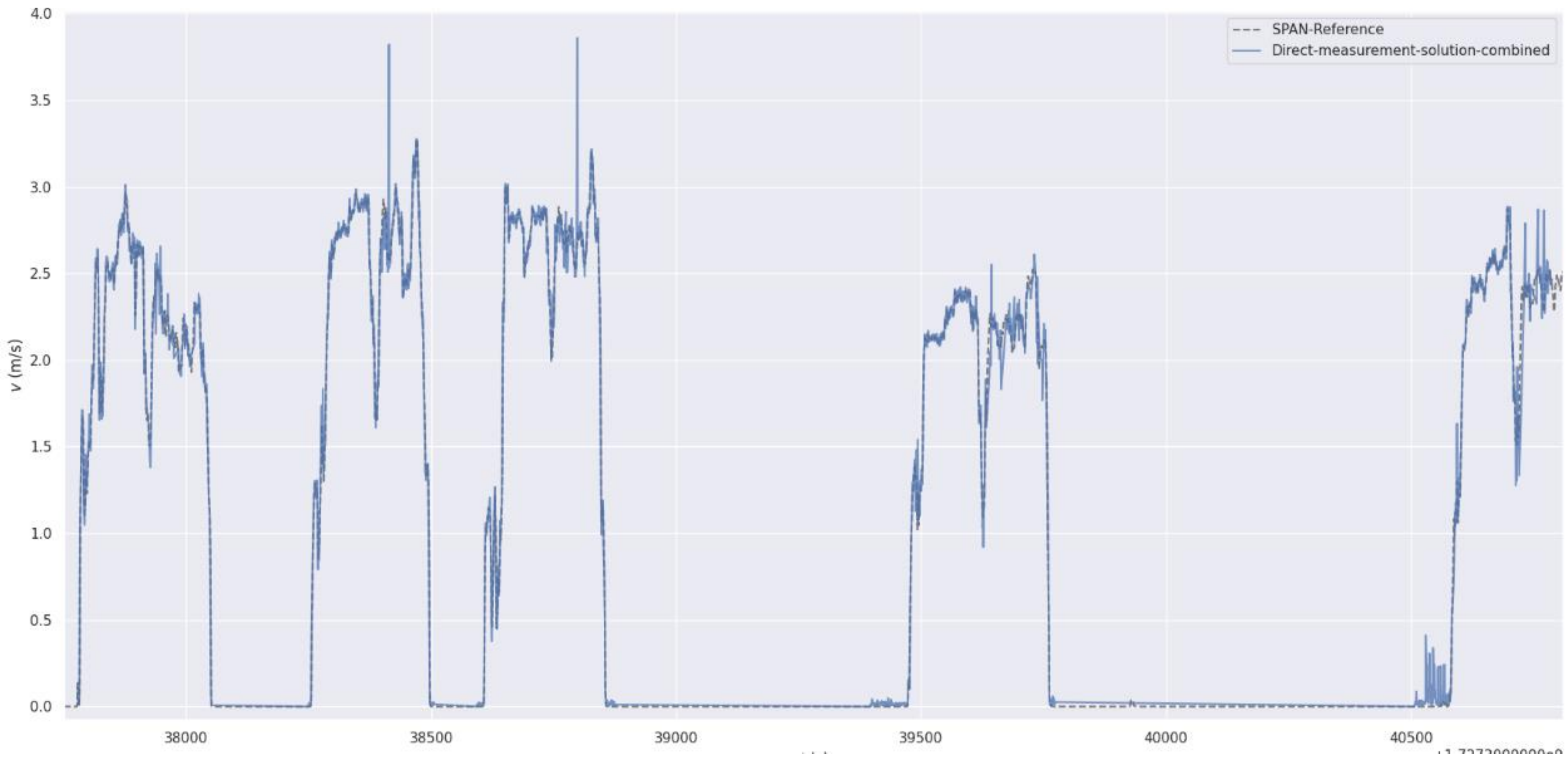
Field trial results

- Standard deviation for pose variables over a moving window
  - Flir values from final field trials
  - ToF values from first tractor tests
- Pose variables exhibit very low noise and seem to fulfil the set targets for relative tractor trailer pose estimate



Field trial results

- Relative velocity estimate
  - Δv



Field trial results

Functional performance:

- PAD worked flawlessly for 20-30Hz frame rates for real-time, and 80Hz for recording
- There is no observable latency between visualization output and the seeder movement

Environmental aspects:

- No significant issues were observed in terms of PAD robustness
  - PAD appeared to tolerate mechanical stress, vibrations etc well.
- Main concerns are the ambient light and dust and dirt.

Conclusions

- Marker solution works well
  - During field trials, the markers remained rather clean
  - The used geometry is practical, not optimal
- Camera based relative seeder pose estimation is remarkably low noise and very precise
  - The main challenge for the approach can be seen in the absolute orientation/attitude estimation given by the tractor side GNSS-IMU system
    - Dual-antenna baseline and placement practical, not optimal
- GNSS-IMU fusion tested with Aux-IMU
  - Does not address the most pressing error sources
    - In the future, could be utilized more for extra accuracy

Conclusions

- Calibrations are a rather significant source for errors
  - And can be difficult to get good enough
    - For commercial solution, calibration jigs etc would be beneficial
- Markers still ‘intermediate step’
  - SLAM, CAD models could be utilized in commercial products instead of markers
- The approach can be seen easily adapted to a variety of tasks
  - Any logistics involving articulated vehicles
    - E.g. parking or hooking up (hitching) a trailer
  - Variety of agriculture solutions, e.g. multi-arm fruit picking machines
  - Docking and vessel approaches

  $\Rightarrow$ Autonomous operations require this type of solution

Advancing together

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