Development of a three dimensional wireless muometric navigation system

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Muographers 2026, 2026.06.02.
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Supported by the eköp-25 university research scholarship program of the ministry for culture and innovation from the source of the national research, development and innovation fund.

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1. Introduction

Motivation

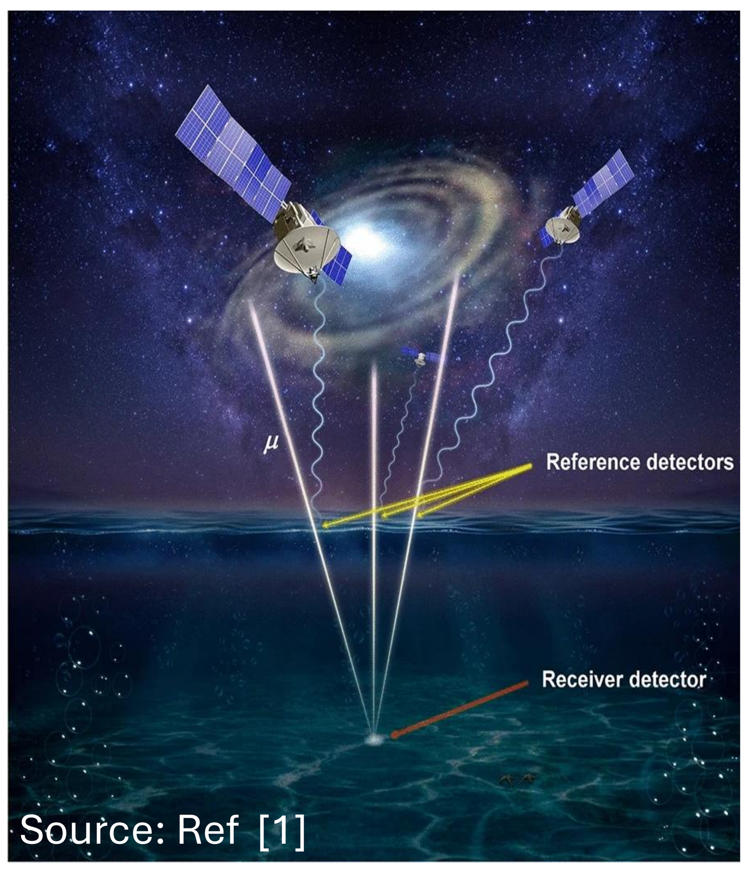
- Positioning where satellite navigation is unavailable: indoor, underground, and underwater navigation
- Ubiquitous highly penetrative muons can reach places where even radio waves can not reach

Principles

- Determine the position of a client's receiver within the coordinates defined by reference detectors
- Methods: ToF (time of flight) or AoA (angle of arrival)

Assumptions for wireless AoA positioning

- References: known position and orientation, good angular resolution
- Receiver: unknown position. Goal is to determine its position and follow its motion
- Limited, wireless, non-synchronized communication channel



Visualization of the concept of muometric positioning utilizing cosmic-ray muons

2. Past results [2]

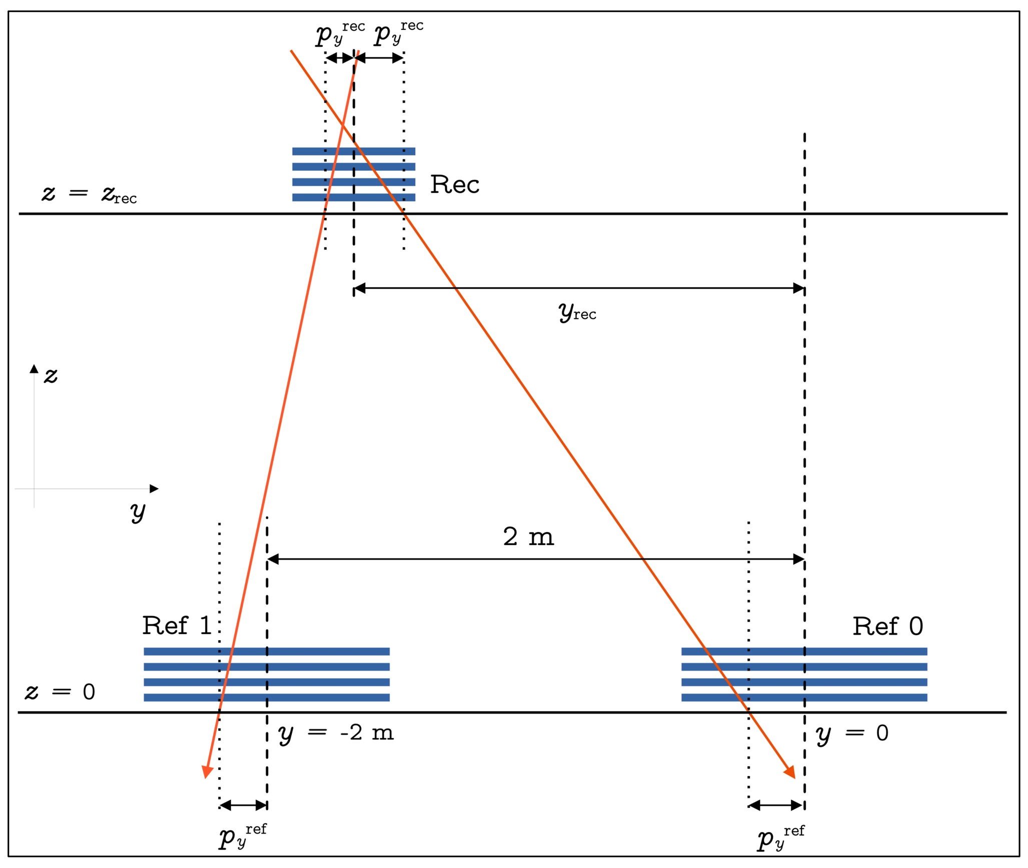
- Two-dimensional wireless muometric navigation system using MWPCs
- 1 Reference and 1 Receiver
- 2 configurations tested with different angular resolution
- cm level positional accuracy reached

Positional accuracy	Vertical separation	Angular resolution
3.9 cm	2.4 m	~15 mrad
3.0 cm	3.3 m	6-8 mrad

Reference (above) and Receiver (below) of the two-dimensional navigation system

3. New three-dimensional navigation system

- 2 References and 1 Receiver, all of them built from MWPCs
- Receiver consists of 4 pieces of 40 cm x 40 cm MWPCs
- References consist of 4 pieces of 80 cm x 80 cm MWPCs each
- ~30 mrad angular resolution of References
- ~7 m vertical separation between References and Receiver
- Orientation of Receiver is aligned with References



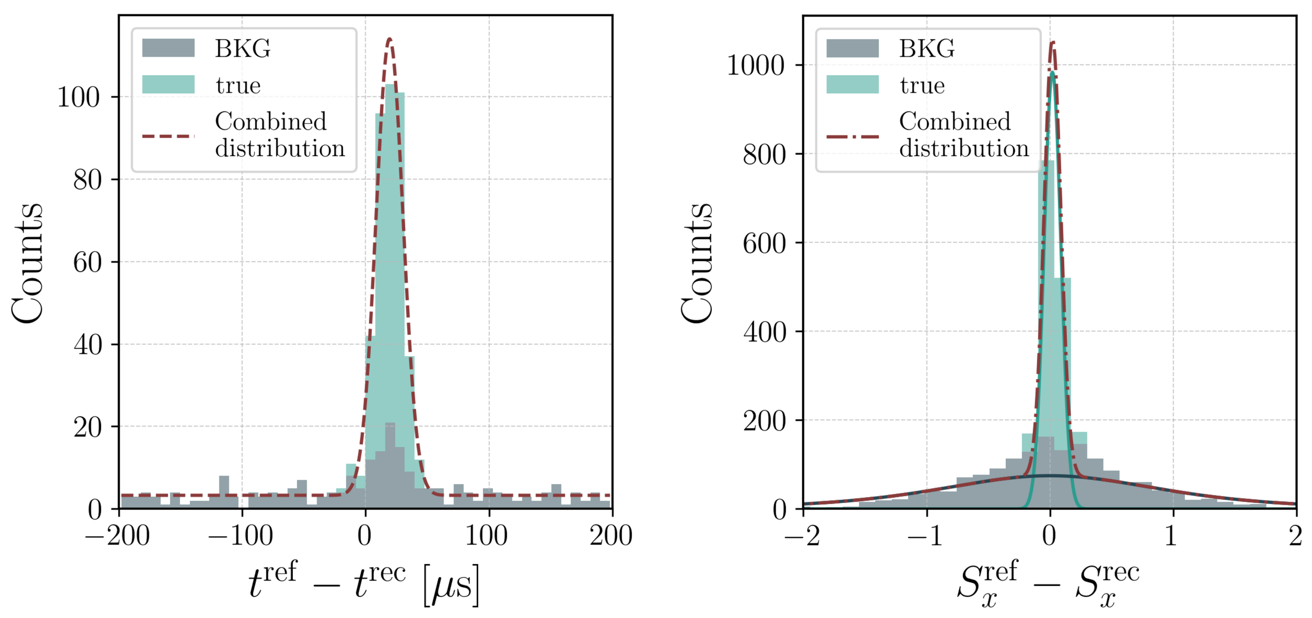
Conceptual view of the three-dimensional navigation system with the References below and the Receiver above. Orange lines indicate examples of muon tracks

4. Matching tracks

- Match tracks between References and Receiver based on timing information.
- References and Receivers have independent readout systems
- Synchronization is reached and maintained with „Cosmic Timing Calibration (CTC)" [3]
- Muon tracks are used both for synchronizing the clocks and positioning the Receiver
- Muon tracks from a Reference and the Receiver are matched if they are within a verification time window T_W
- As cosmic muon flux is limited ~100 Hz/m^2 $\rightarrow T_W \lesssim 0.1$ ms

5. Background rejection

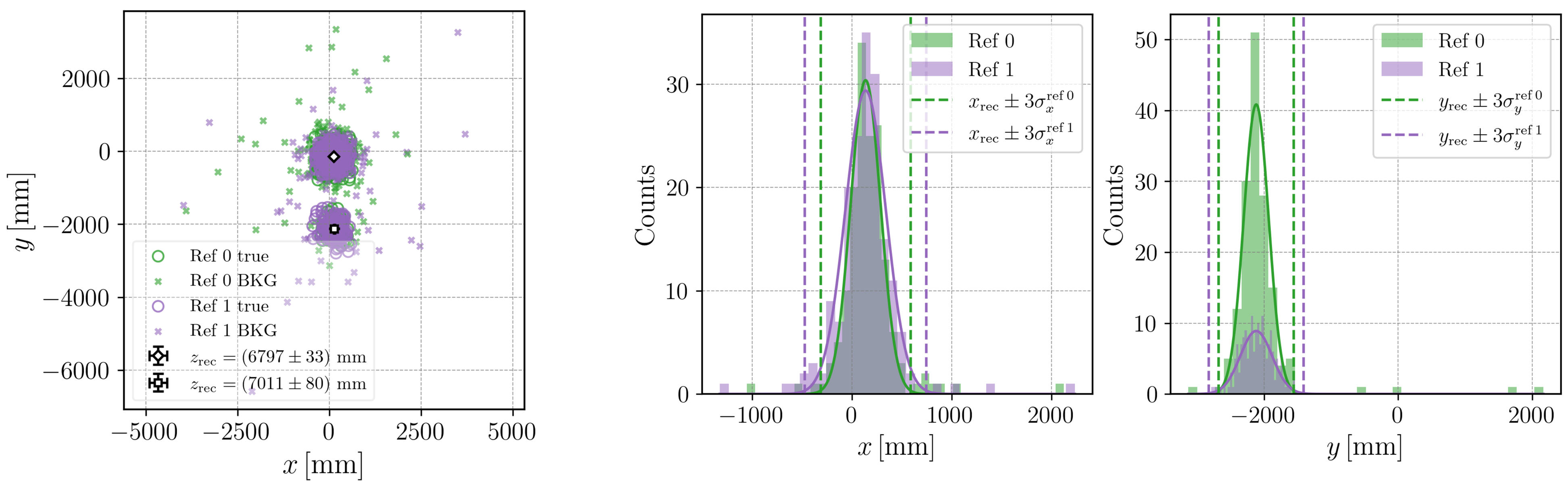
- Using time and slope difference between Reference and Receiver
- Fit Gaussian + background on time/slope difference distribution
- $D^2 := \frac{(t^{ref} - t^{rec})^2}{\sigma^2_{\Delta t}} + \frac{(s_x^{ref} - s_x^{rec})^2}{\sigma^2_{\Delta s_x}} + \frac{(s_y^{ref} - s_y^{rec})^2}{\sigma^2_{\Delta s_y}}$, Reject if $D^2 < \chi^2_{3;0.01}$



Time and slope difference distribution and the fitted background and gaussian functions

6. Positioning the Receiver and calibrating the References

- From the measurements the Receiver's position can be found via a Least Squares fit.
- Knowing the position the angular resolution of the References can be recovered from the spread of measurements around the position.
- Background can further be rejected via Sigma Clipping the measurements



The fitted Receiver position with white and the intersections of the measured muon tracks with the fitted z_{rec} plane with purple and green.

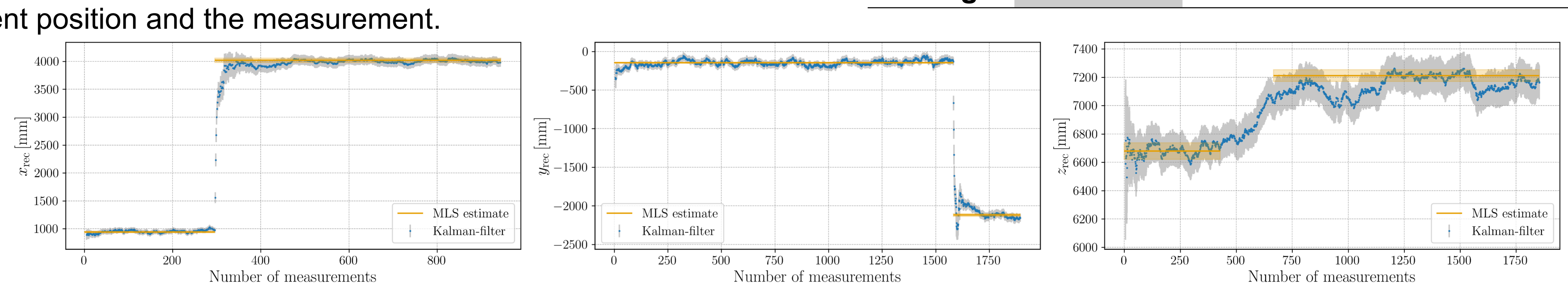
The distribution of muon track intersection coordinates with the fitted z_{rec} plane. All tracks outside the 3σ range are rejected as background and the fit is performed again omitting these measurements.

7. Following the motion of the Receiver

- Follow the motion of the Receiver using a Kalman-filter based algorithm.
- Update the Receiver position with each subsequent measurement.
- Background is further rejected via a consistency check between the current position and the measurement.

8. Results

	Vertical separation	Vertical positional accuracy	Lateral positional accuracy
Standing	~ 7 m	3-10 cm	1–3 cm
Moving		25-50 cm	10-20 cm



The estimated coordinates of the Receiver based on subsequent measurements. The three figures show three different coordinates. The figures correspond to distinct sessions. In each session only one coordinate of the Receiver (the one which is depicted here) was suddenly changed, while the other two were left unchanged. Yellow lines show a least squares estimate of the position using all measurements of the session.

References

[1] Tanaka, H.K.M. Muometric positioning system (μPS) with cosmic muons as a new underwater and underground positioning technique. *Sci Rep* **10**, 18896 (2020). https://doi.org/10.1038/s41598-020-75843-7

[2] Varga, D., Tanaka, H.K.M. Developments of a centimeter-level precise muometric wireless navigation system (MuWNS-V) and its first demonstration using directional information from tracking detectors. *Sci Rep* **14**, 7605 (2024). https://doi.org/10.1038/s41598-024-57857-7

[3] Tanaka, H.K.M. Cosmic time calibrator for wireless sensor network. *Sci Rep* **13**, 5951 (2023). https://doi.org/10.1038/s41598-023-32262-8