Free-space laser links for frequency transfer between fast-moving optical clocks

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S.F.E. Karpathakis, A.S. McCann, S. McSorley, and S.M. Walsh.

The University of Western Australia

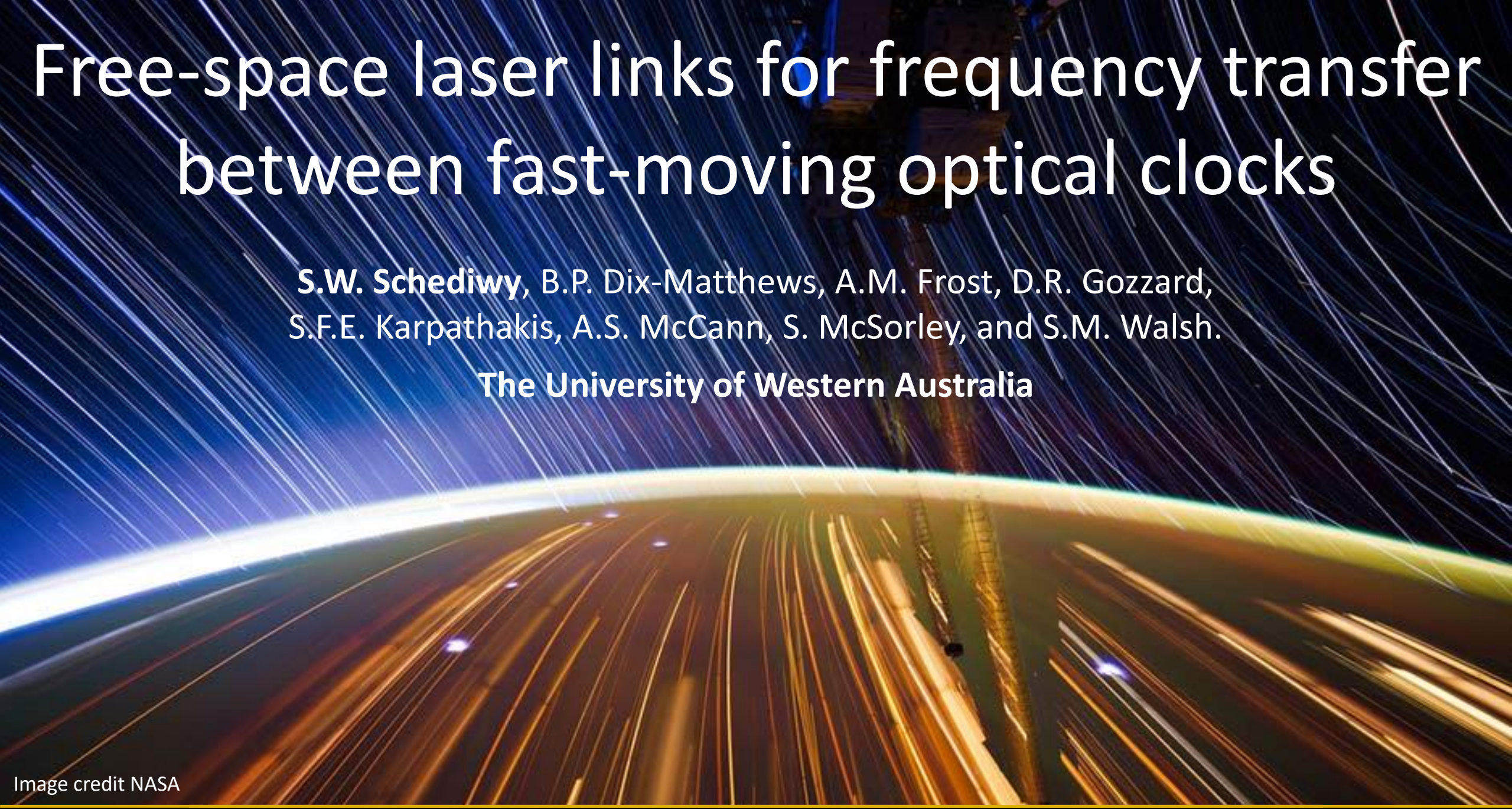

Image credit NASA

Presentation Overview

- 1. Motivation: The need for frequency transfer between fast moving objects
- 2. Background: Precision metrology through the turbulent atmosphere
- 3. Current work: Preliminary results for transfer between fast moving objects
- 4. Next steps: Future work and collaboration opportunities

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Frequency Transfer between Fast Moving Objects

- Why conduct frequency transfer over **free-space links** instead of over optical fibre links?
  1. When using fibre is impractical or impossible
  2. Applications that involve a fast-moving elements comprising the link

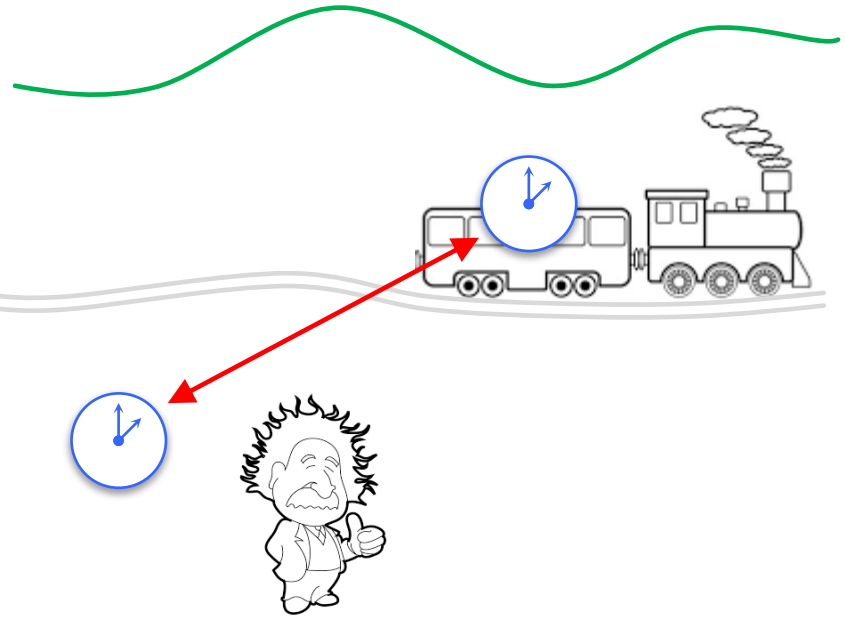
- Fast: $\nu_D \approx \pm 20$ MHz, **v ≈ 60 m/s** (≈ 200 km/h)
  - Dynamic terrestrial links: 2 examples

- Very fast: $\nu_D \approx \pm 5$ GHz, **v ≈ 7,000 m/s**
  - Ground-to-space links: 2 examples

Frequency Transfer between Fast Moving Objects

1. Frequency transfer between transportable, **moving** ground-based clocks ($\nu_D \approx \pm 20$ MHz)
   - *Application example:* Direct measurement of Einstein's famous special relativity thought experiment (time dilation on a train)

2. Frequency transfer between transportable **stationary** ground-based clocks ($\nu_D \approx \pm 20$ MHz)
   - *Application example:* Chronometric leveling surveys via airborne relay for Earth science, geophysics, and environmental monitoring



[1] Dix-Matthews, et al. *Optics Express* **31** (2023) 15075.

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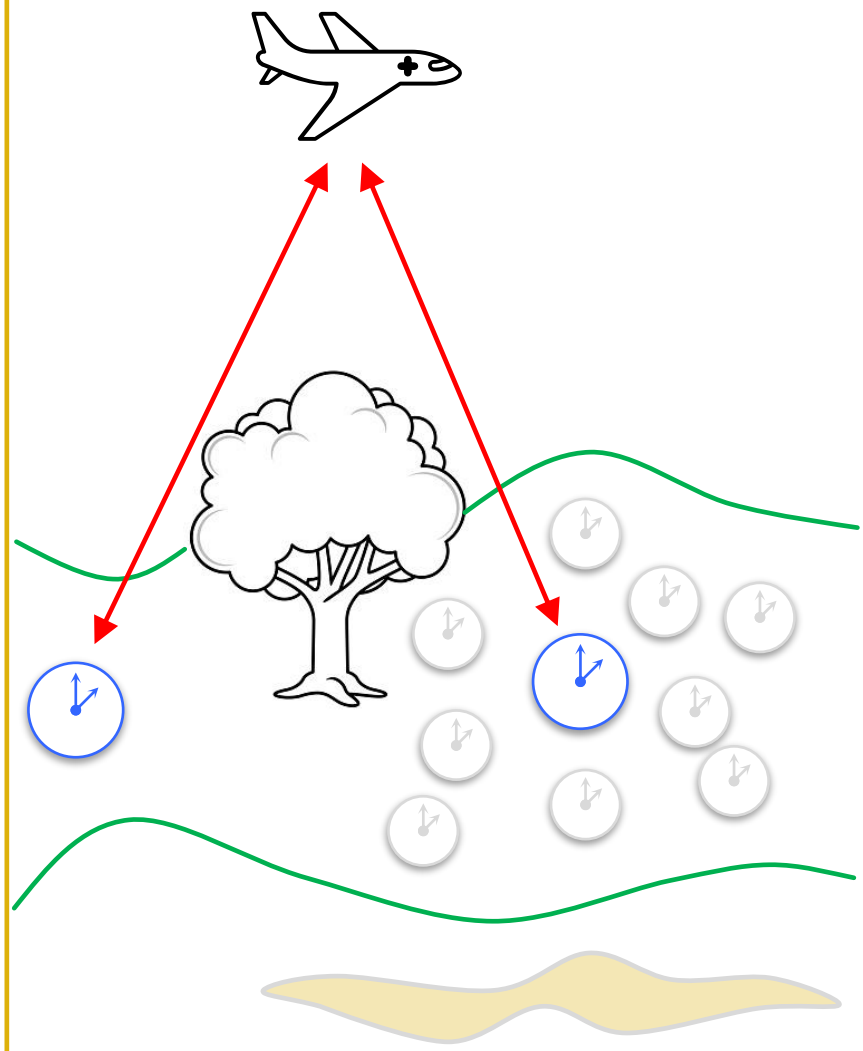


[1] Dix-Matthews, et al. *Optics Express* **31** (2023) 15075.

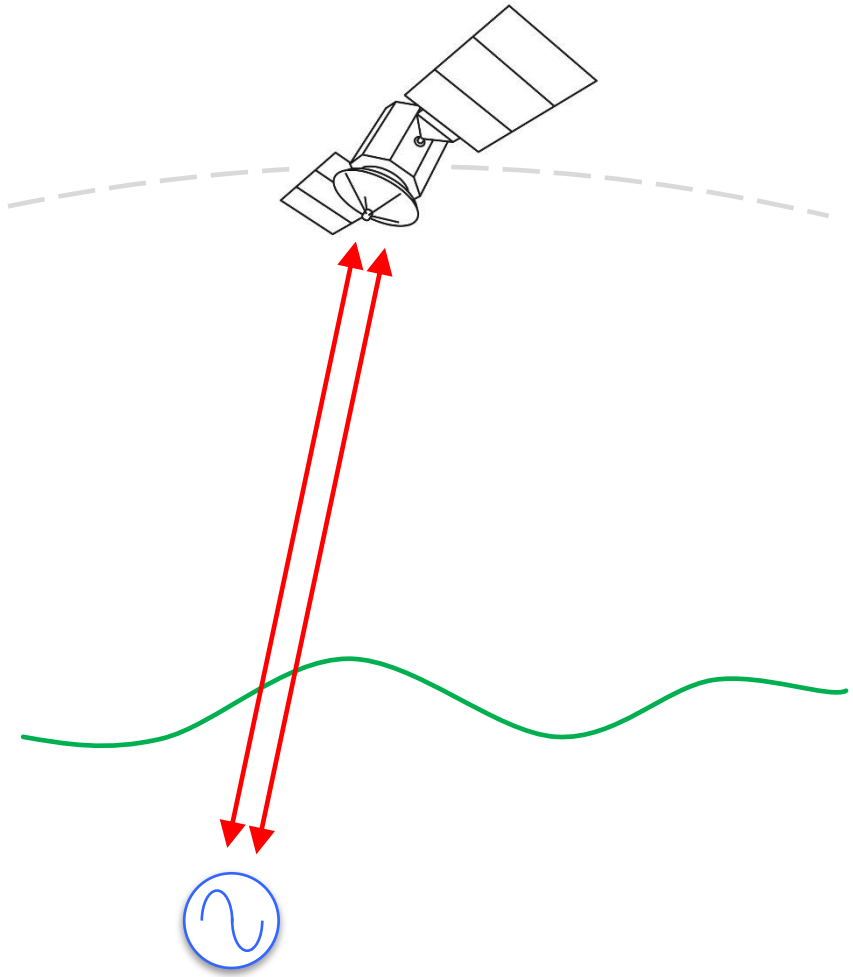
Frequency Transfer between Fast Moving Objects

3. Frequency transfer **reflected** off a satellite in space (no clock required): $\nu_D \approx 2\times \pm 5$ GHz
   - *Application example:* Ultra-precise satellite orbit determination to improve the accuracy of the Global Geodetic Reference Frame

   [2] Dix-Matthews, et al *Physical Review Applied* **19** (2023) 054018.

4. Frequency transfer between ground- and **space-based** optical clocks: $\nu_D \approx \pm 5$ GHz
   - *Application example:* Tests of General relativity (local position invariance), fundamental physics (dark matter, var. in fundamental constants)

   [3] Gozzard, et al. *Physical Review Letters* **128** (2022) 020801.



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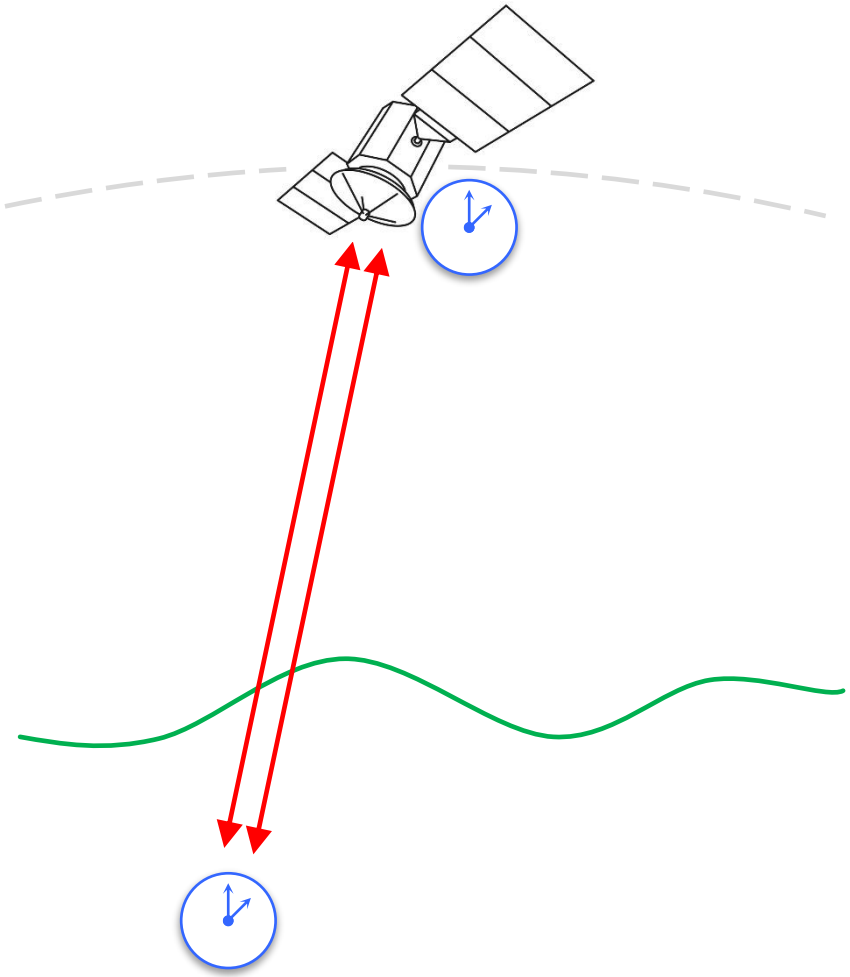

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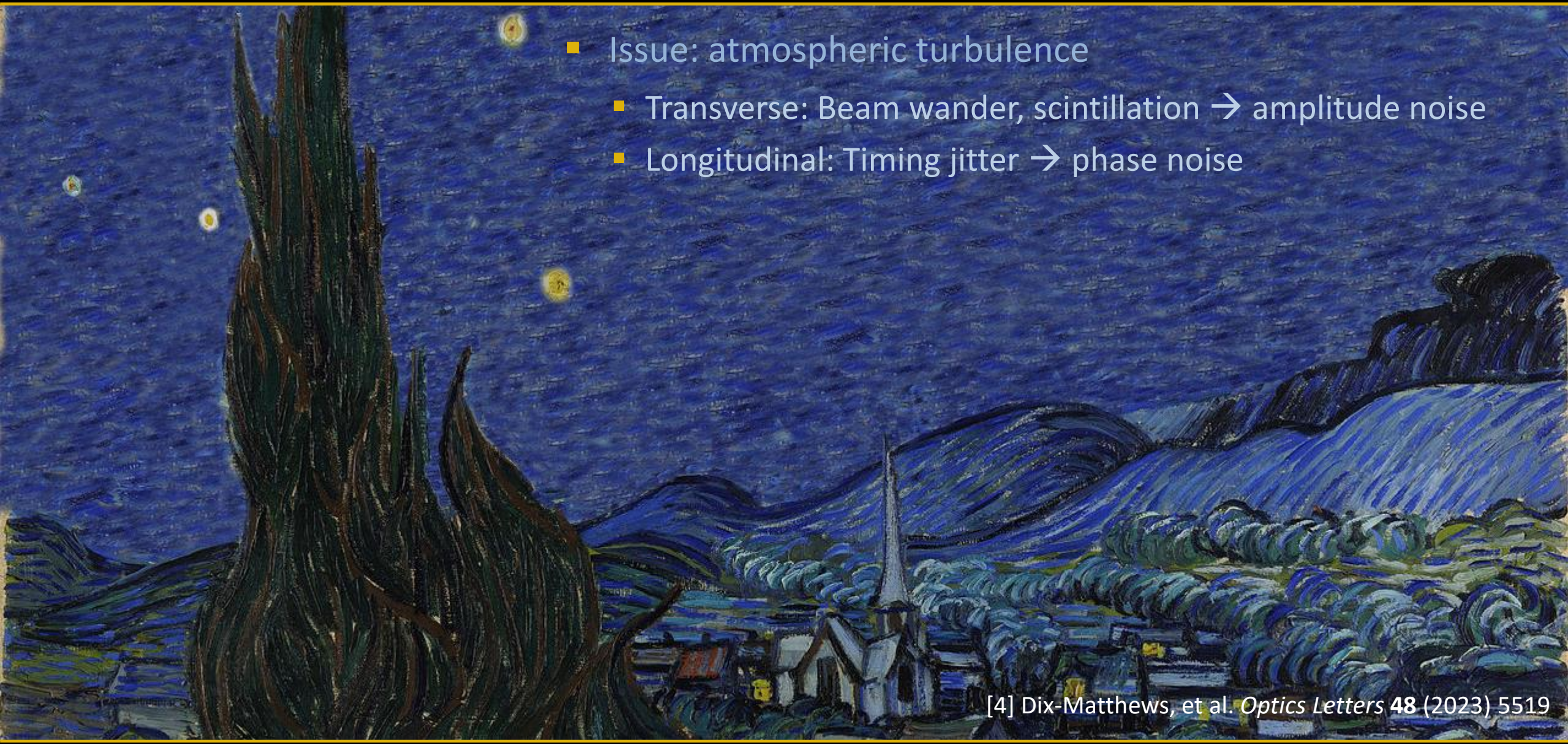
Precision Metrology through Atmospheric Turbulence

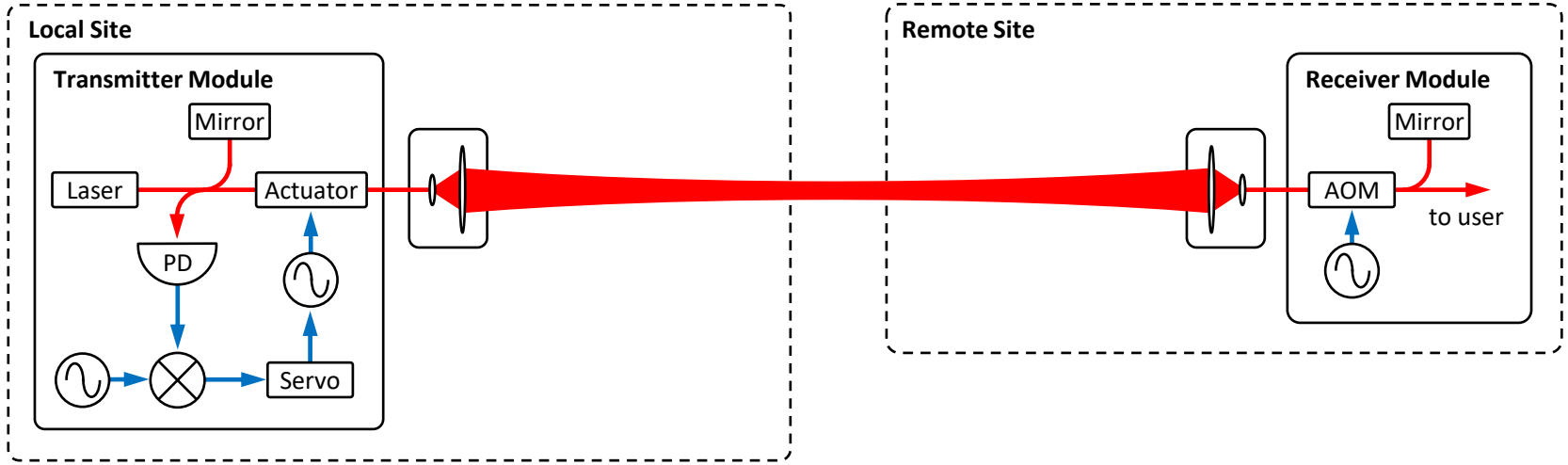


- Issue: atmospheric turbulence
  - Transverse: Beam wander, scintillation → amplitude noise
  - Longitudinal: Timing jitter → phase noise

[4] Dix-Matthews, et al. *Optics Letters* **48** (2023) 5519

Precision Metrology through Atmospheric Turbulence

- Free-space phase-stabilised frequency transfer
  - Single frequency (CW) laser system
- Advantages
  - Better performance
  - Lower SWaP
- Disadvantages
  - Sensitive to deep-fades
  - No time transfer



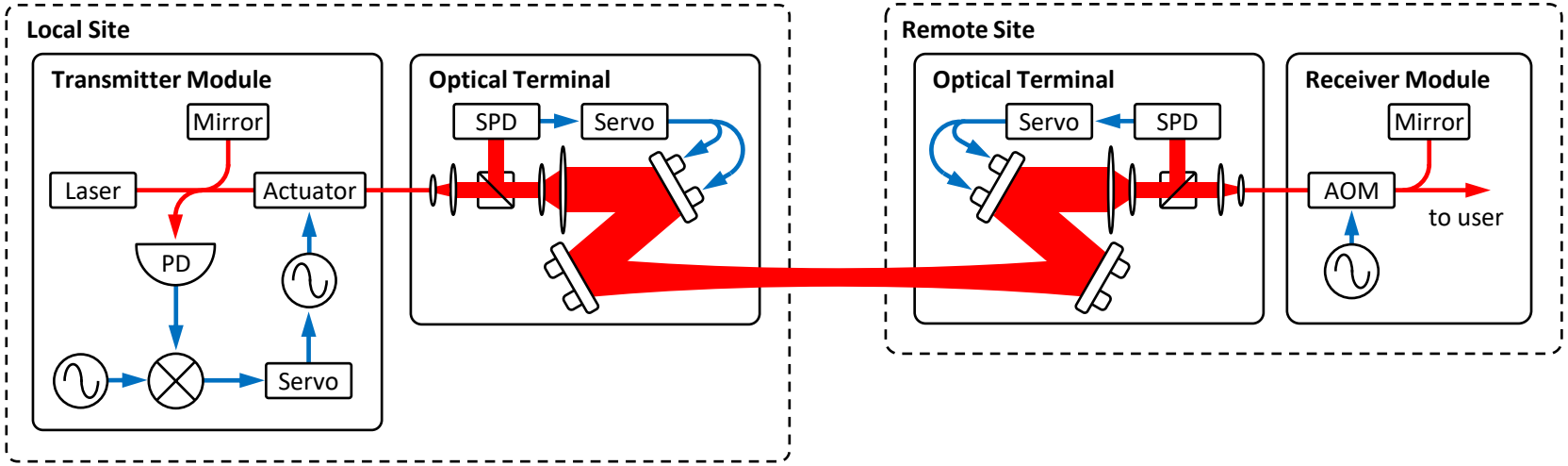
[5] Gozzard, et al. *Physical Review Applied* **10** (2018) 024046

- Phase stabilisation transmitter

- Phase stabilisation receiver

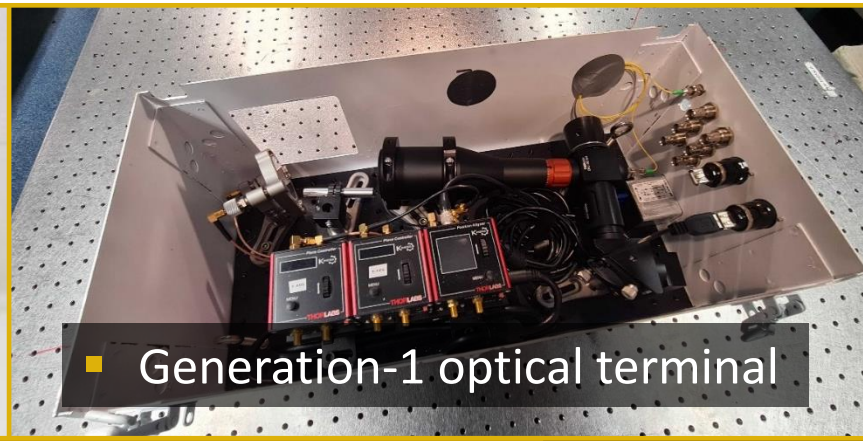
Precision Metrology through Atmospheric Turbulence

- Free-space phase-stabilised frequency transfer with adaptive optics terminals
  - Single frequency (CW) laser system
- Advantages
  - Better performance
  - Lower SWaP
- Disadvantages
  - ~~Sensitive to deep-fades~~
  - No time transfer



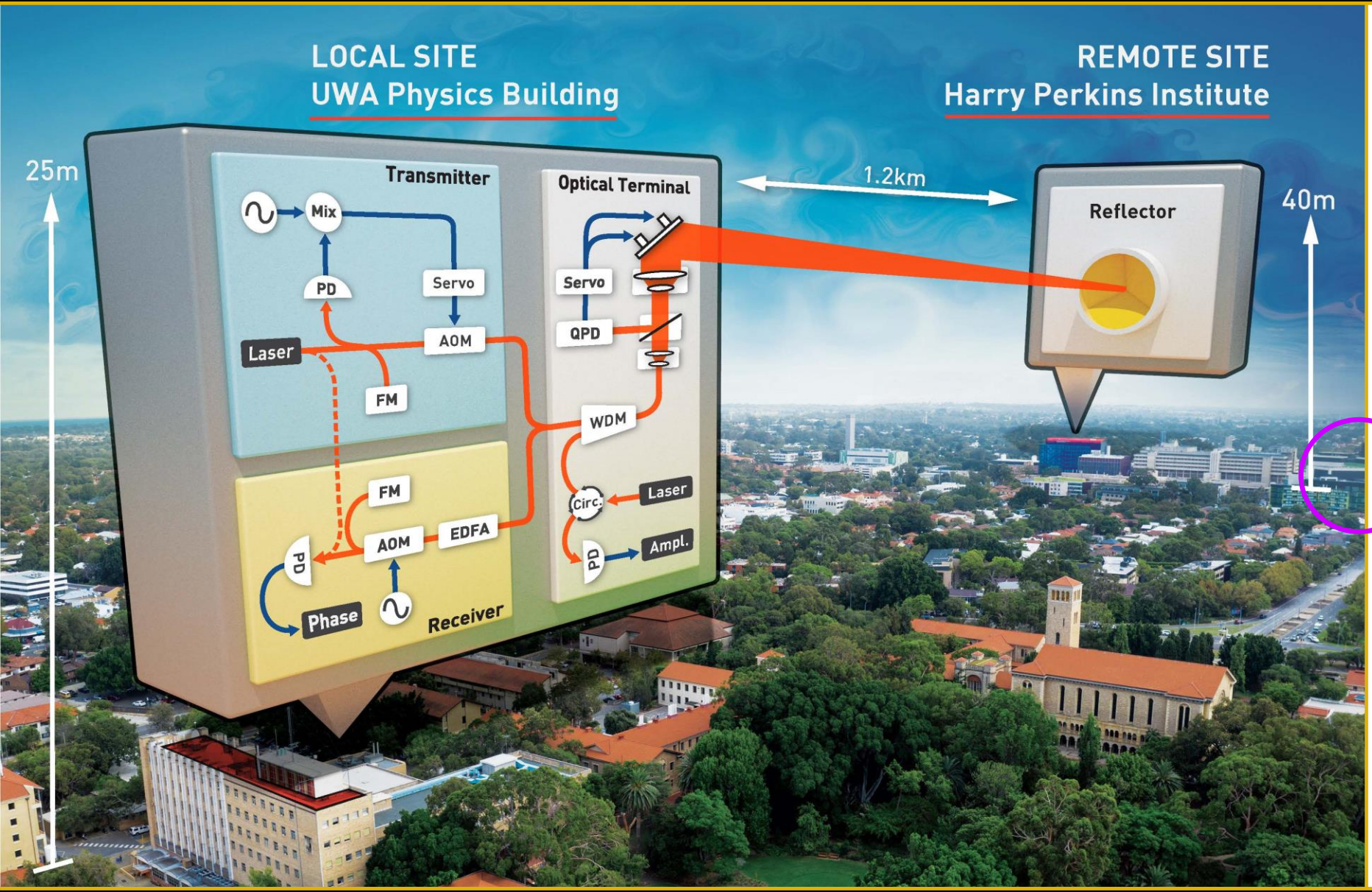
[6] Dix-Matthews, et al. *Nature Communications* **12** (2021) 515

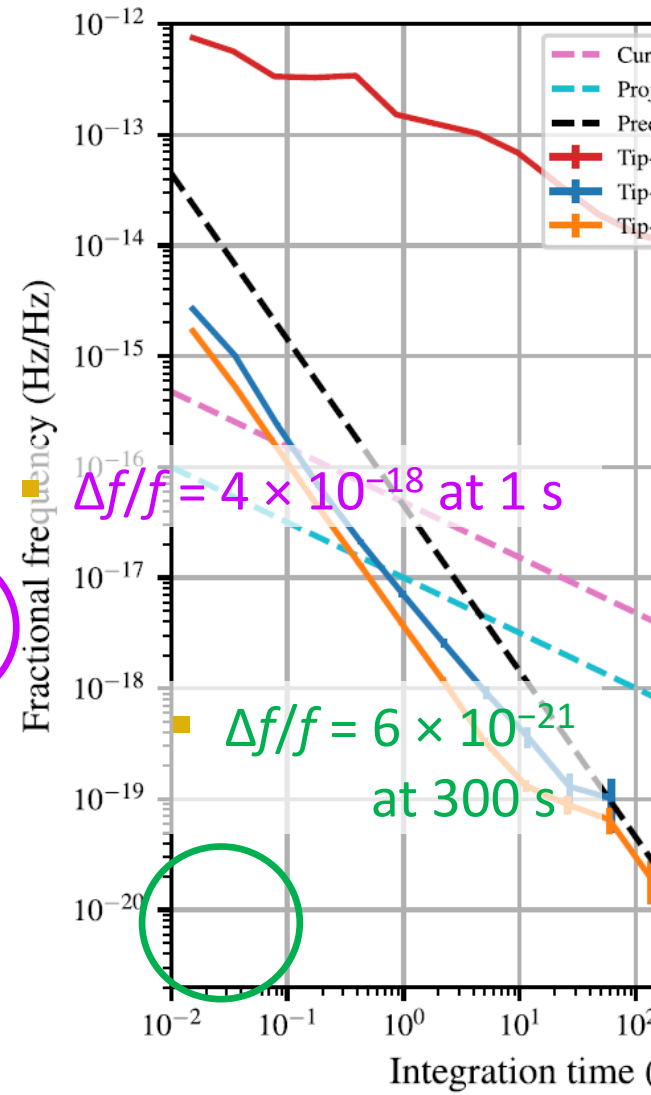
- Phase stabilisation transmitter



- Generation-1 optical terminal

Precision Metrology through Atmospheric Turbulence





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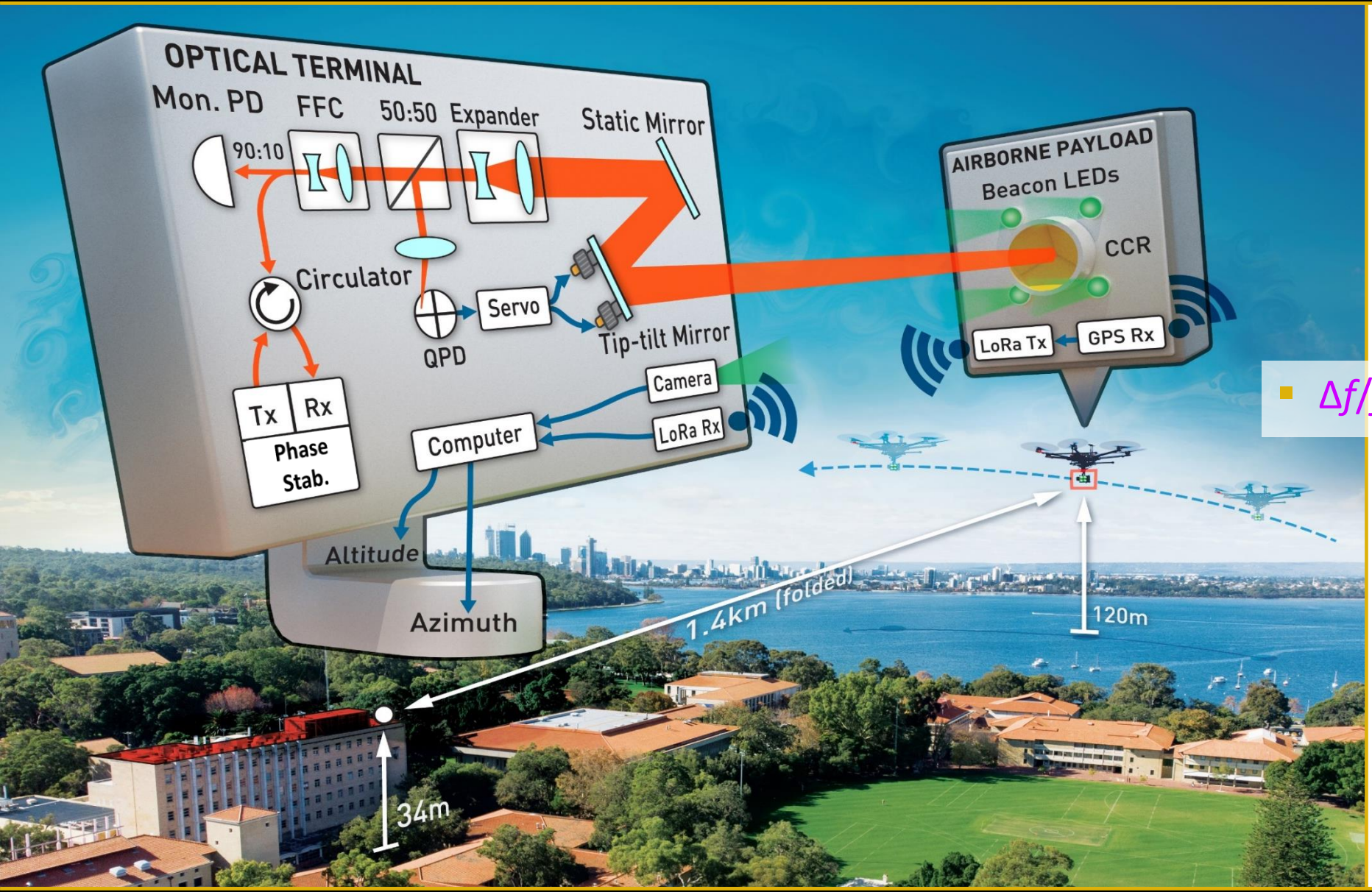
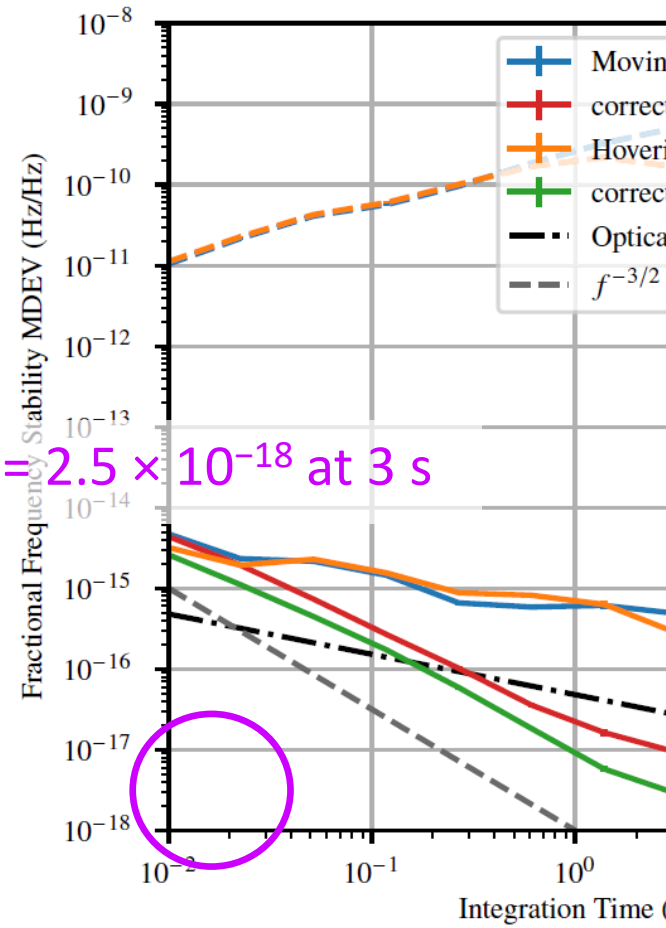
Precision Metrology through Atmospheric Turbulence



- $\Delta f/f = 2.5 \times 10^{-18}$ at 3 s



[7] Walsh, et al. *Scientific Reports* **12**
[1] Dix-Matthews, et al. *Optics Expr*

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Preliminary Results for Fast-Moving Atmospheric Links

- Part 1: Acquisition, tracking, and SMF coupling via aircraft links

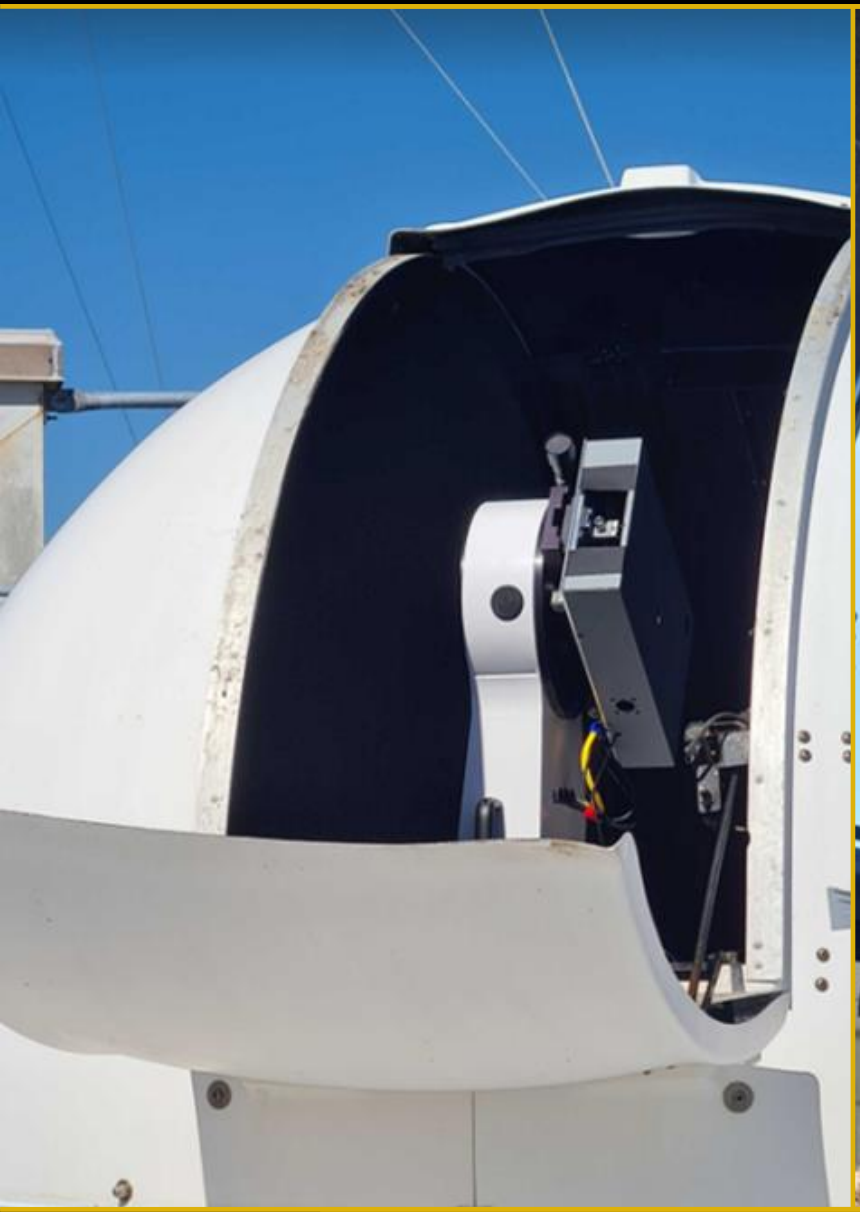
- Fixed wing light aircraft

- WA Police rotary wing aircraft

Preliminary Results for Fast-Moving Atmospheric Links

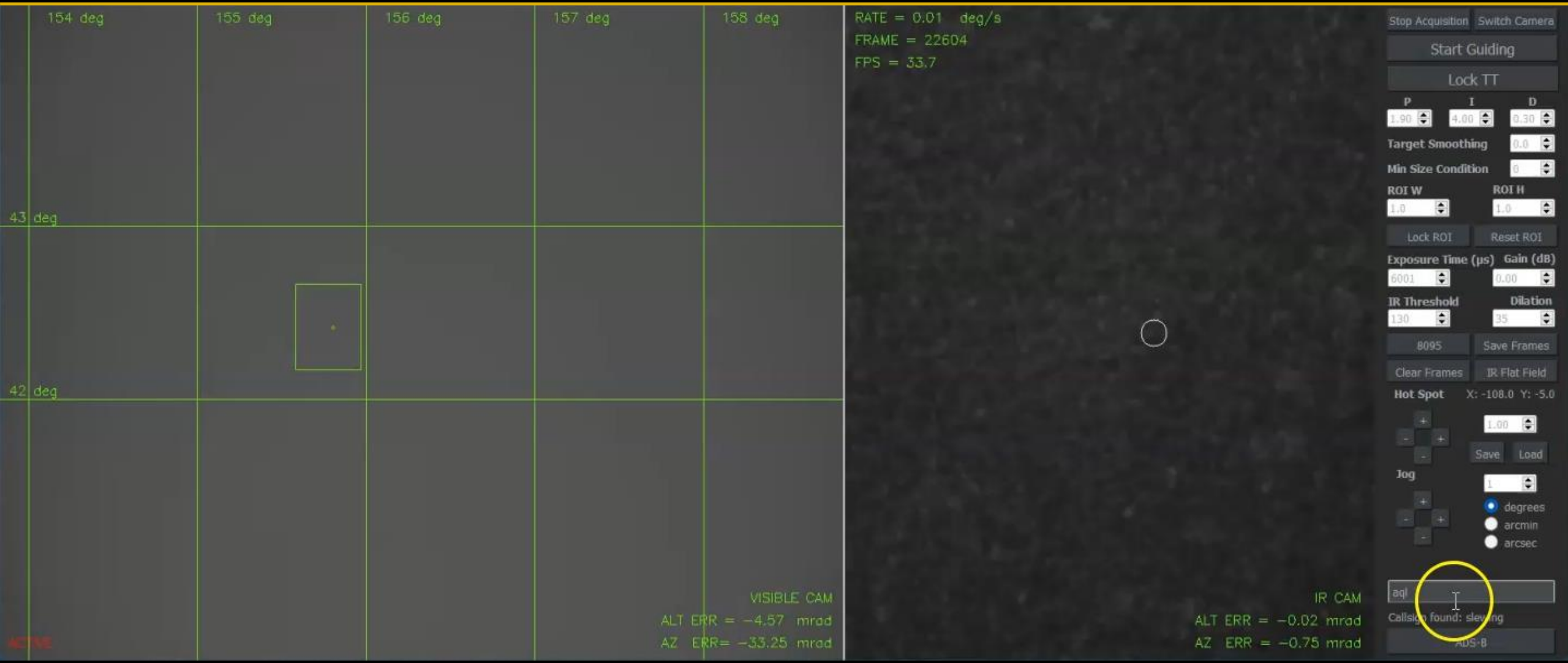
- Fixed wing light aircraft, 10 km folded link length

Preliminary Results for Fast-Moving Atmospheric Links



- Generation-3 optical terminal

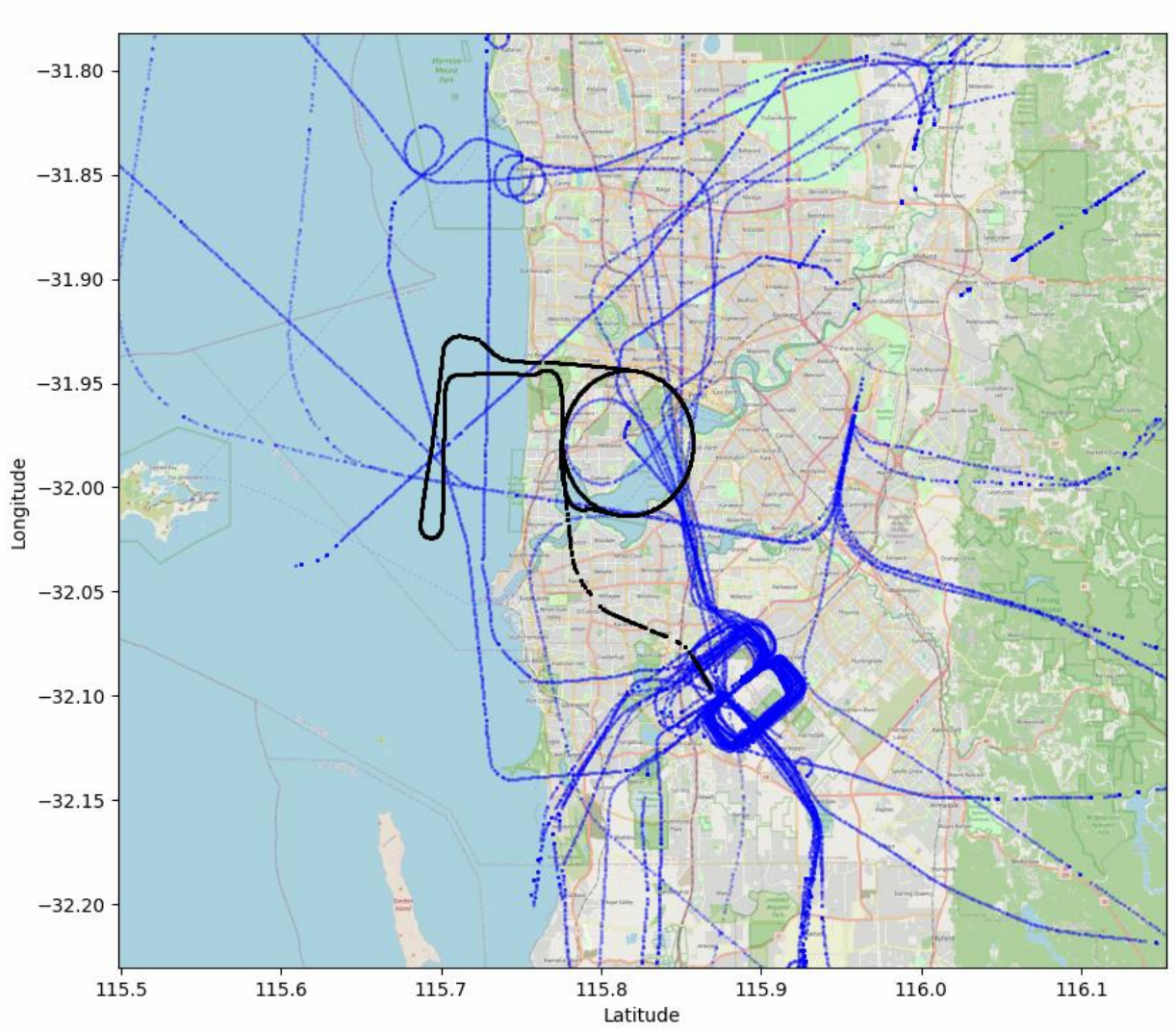
Preliminary Results for Fast-Moving Atmospheric Links

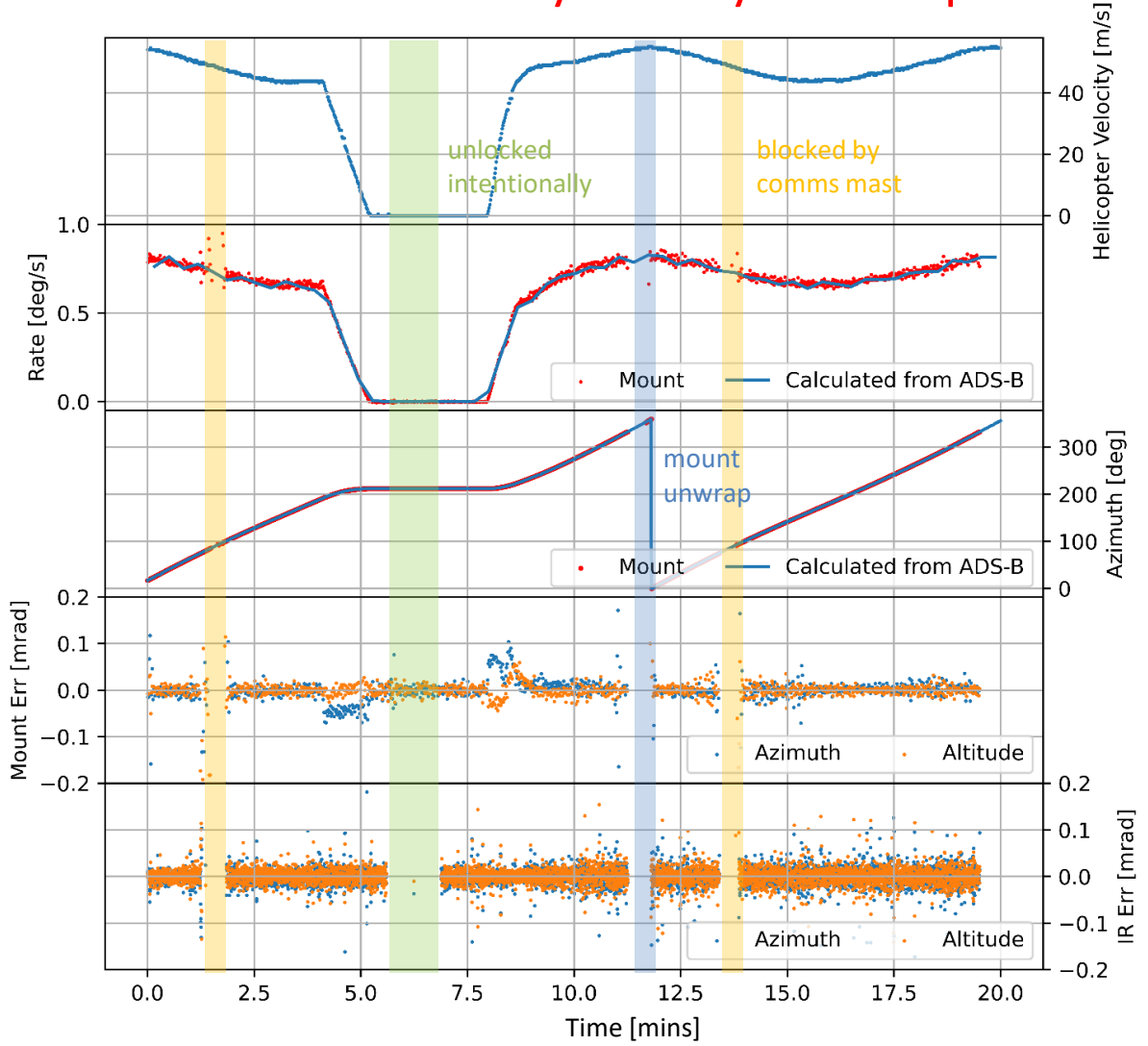


- Four-stage autonomous target acquisition and tracking system

Preliminary Results for Fast-Moving Atmospheric Links

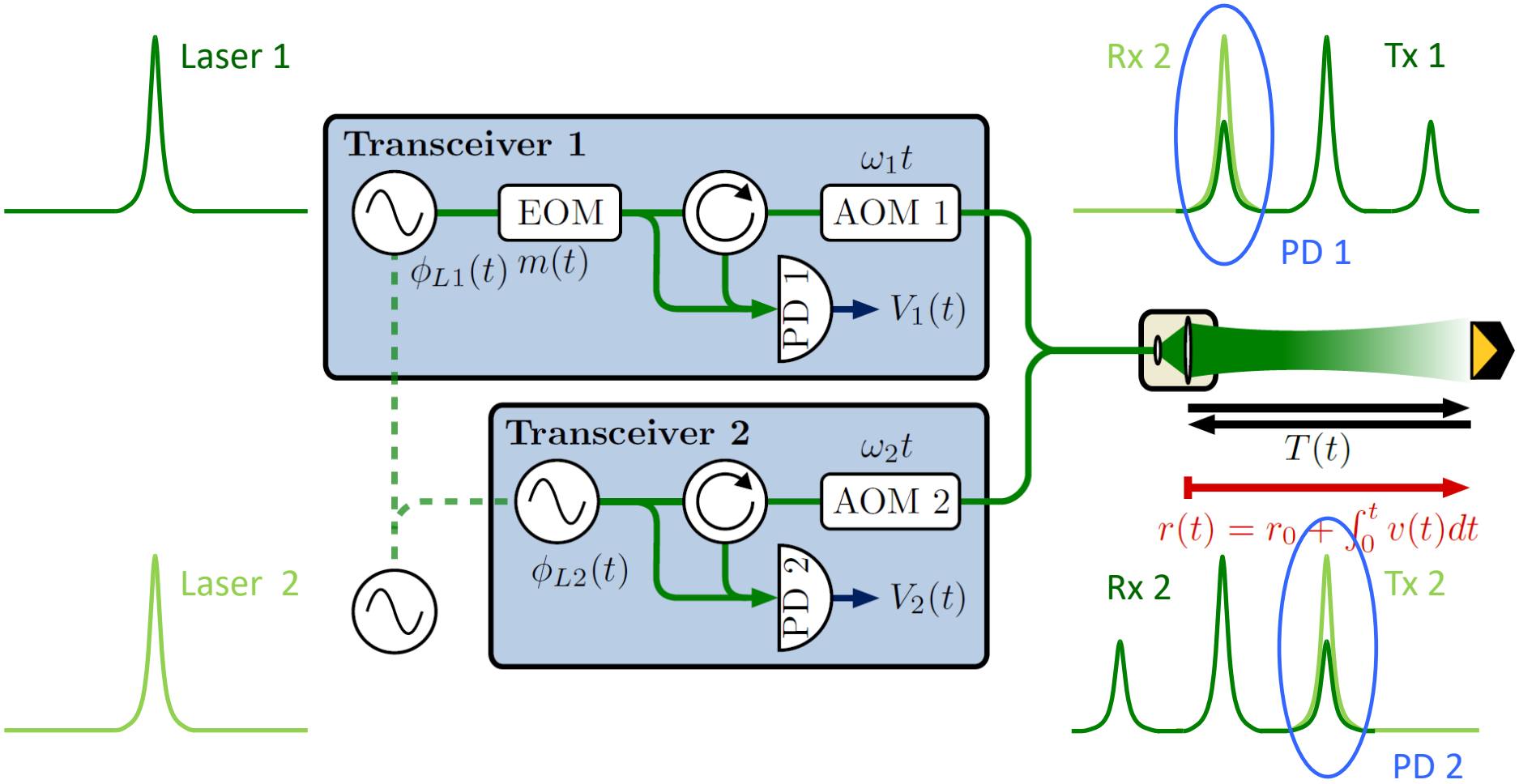
Preliminary work: yet to be published





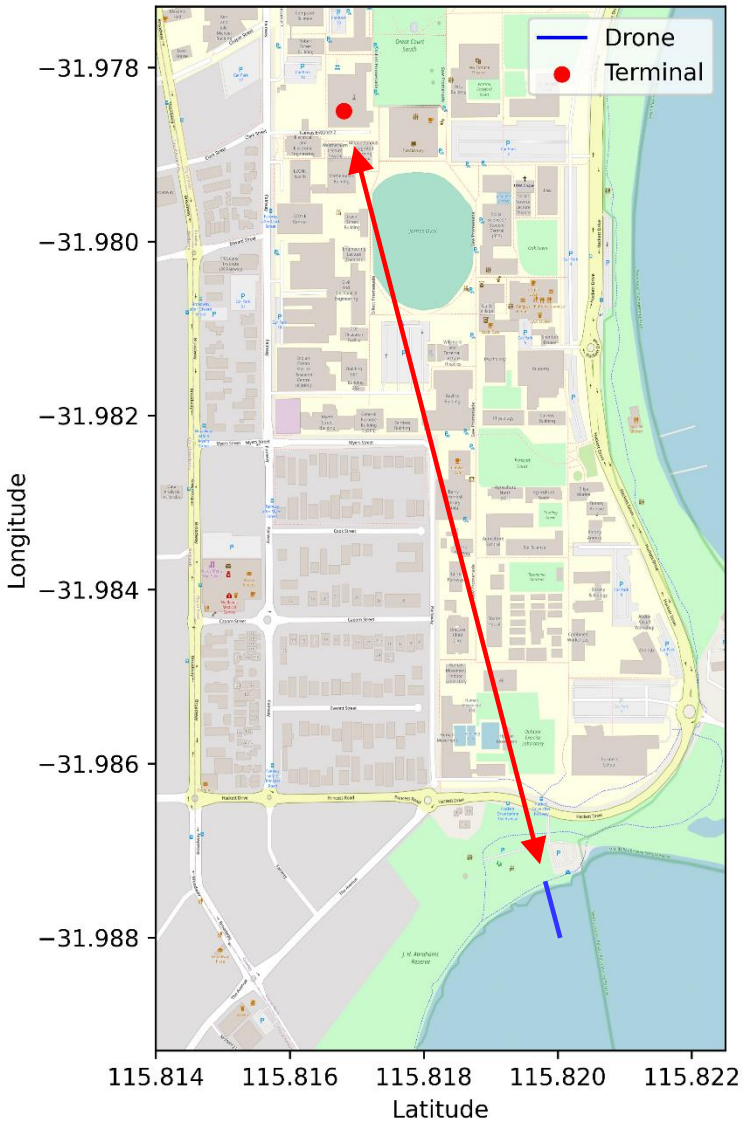
Preliminary Results for Fast-Moving Atmospheric Links

- Part 2: Frequency transfer scheme that can phase-track large Doppler shifts

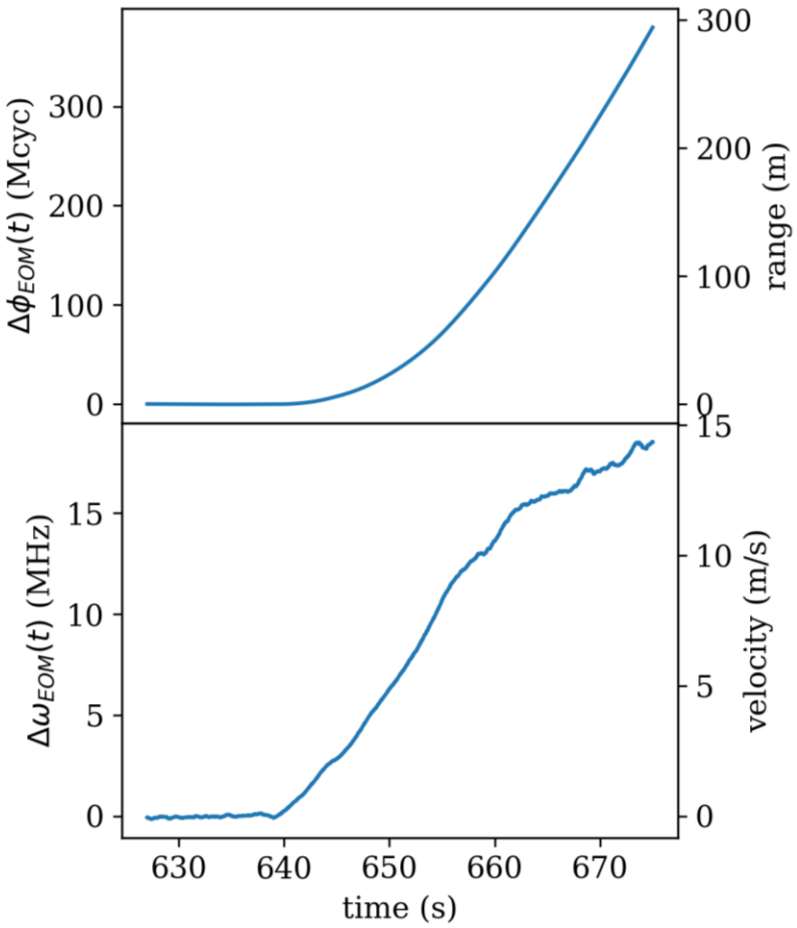


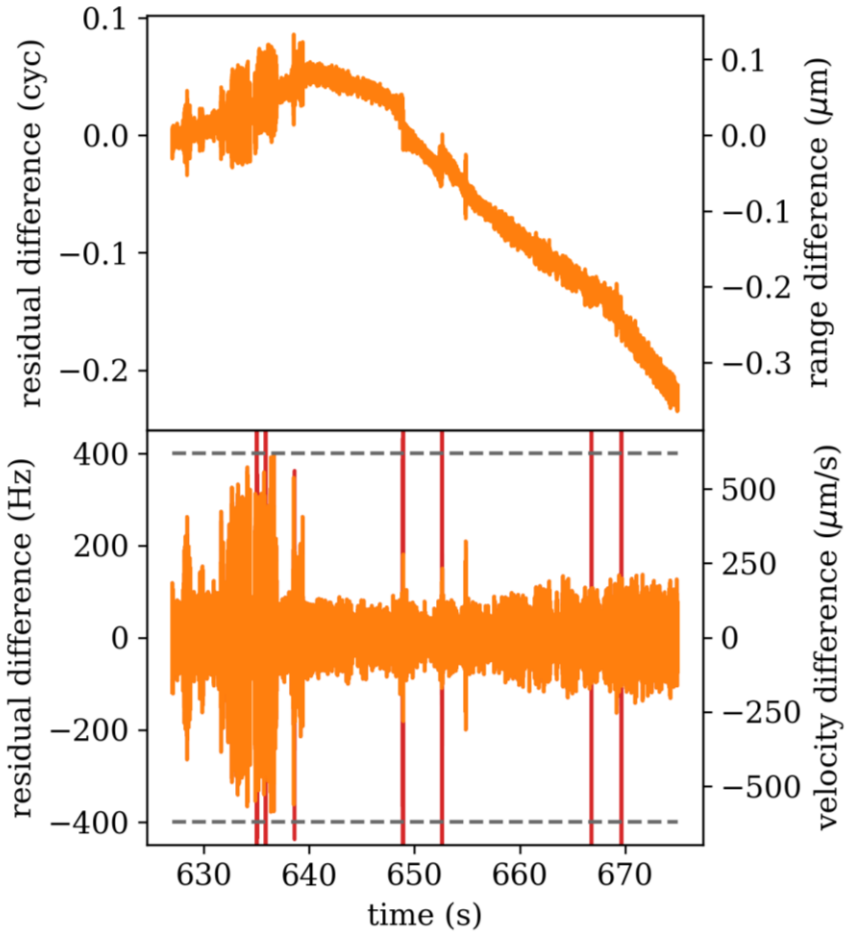
Preliminary work: yet to be published

Preliminary Results for Fast-Moving Atmospheric Links



- Frequency transfer time series data





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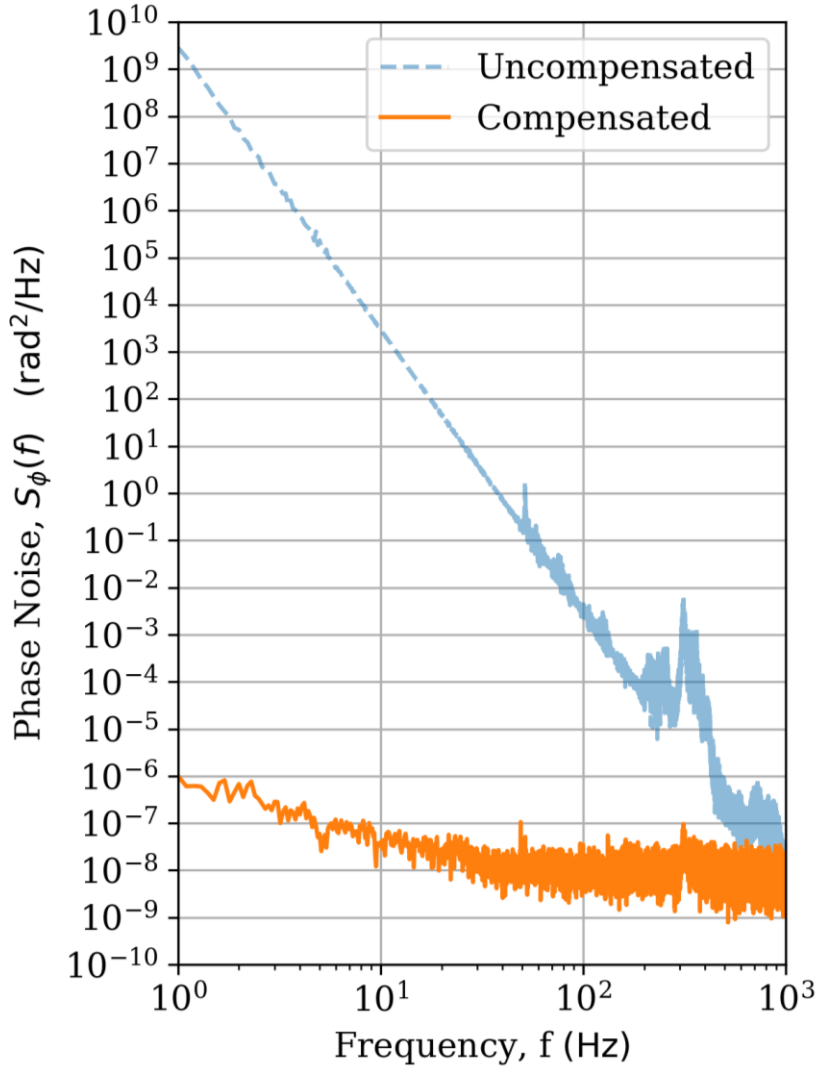

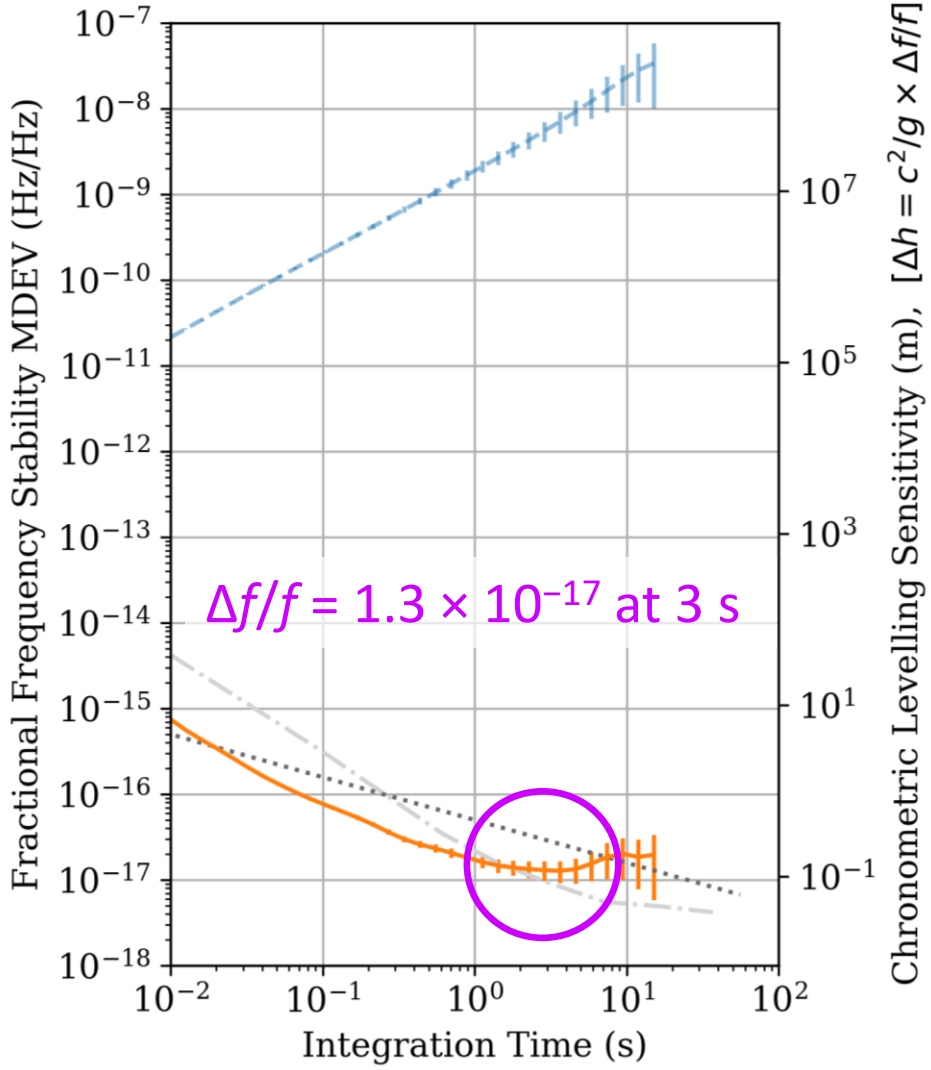

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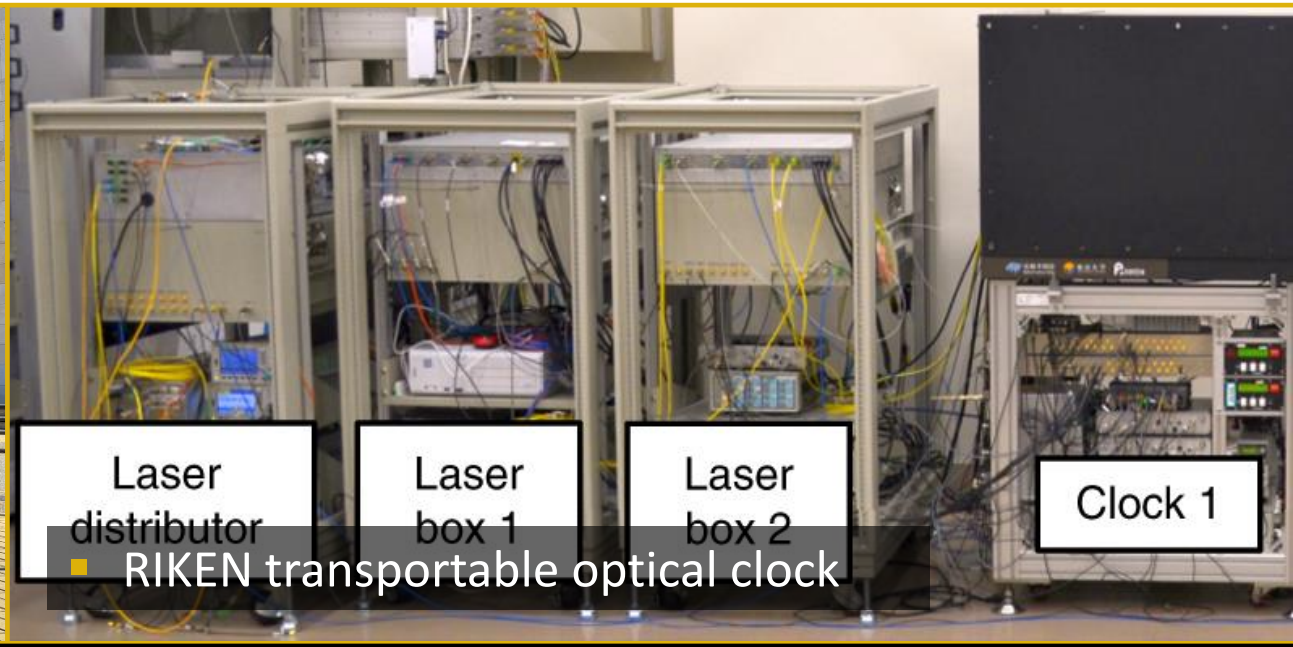
Future Work and Collaboration Opportunities

- **Q1-2024:** Transportable optical clock comparison reflected links via aircraft
  - Towards *Application 2* (aircraft relay) and *Application 3* (reflected space link)
- **Q4-2024:** Point-to-point transportable optical clock comparison via truck/boat
  - Towards *Application 1* (special relativity) and *Application 2* (aircraft relay)

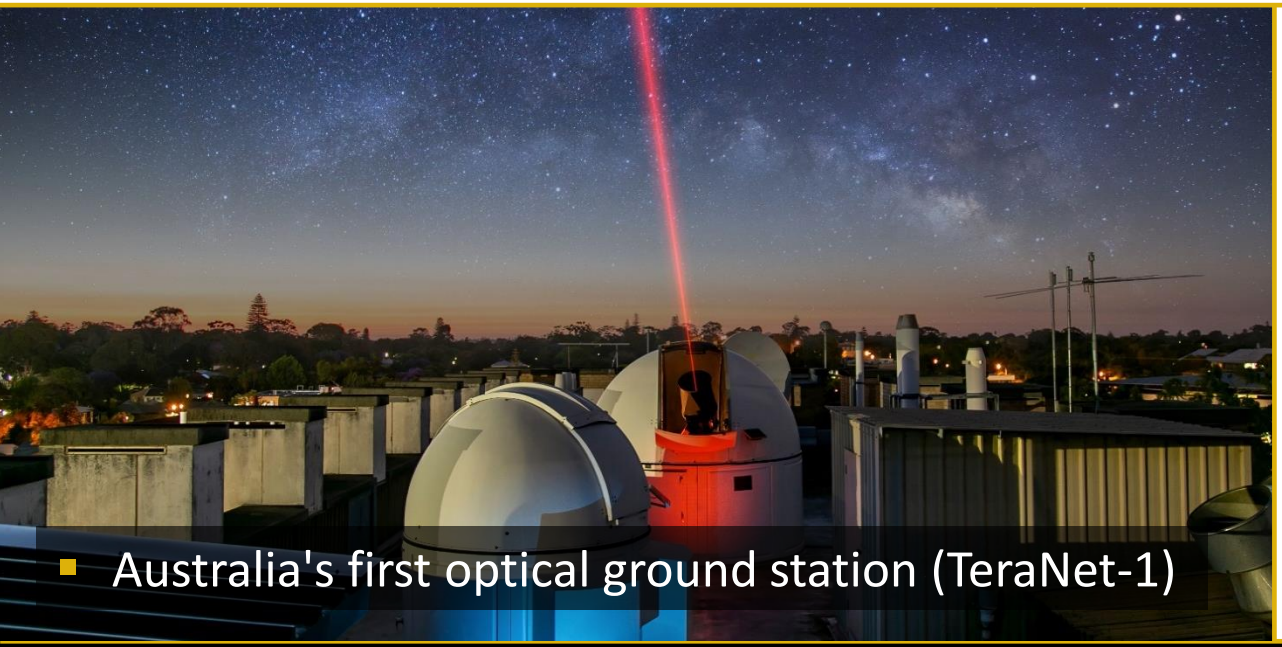
- UWA mobile optical ground station (TeraNet-3)



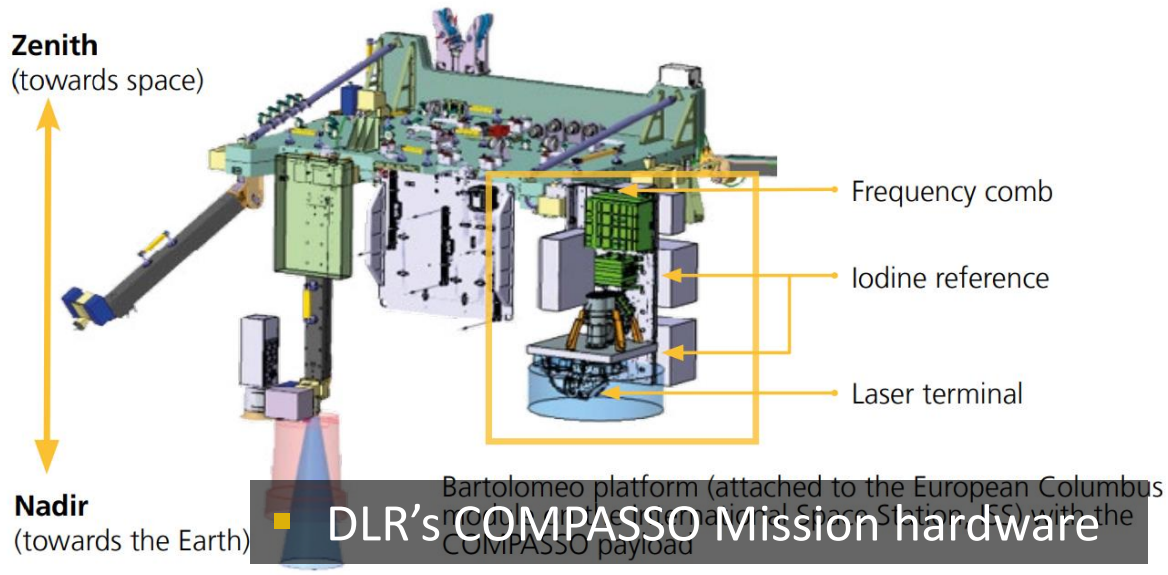
- RIKEN transportable optical clock

Future Work and Collaboration Opportunities

- **2025:** Optical Doppler orbitography using existing a satellite in space
  - First demonstration of *Application 3* to improve the accuracy of the GGRF
- **2026:** Ready to contribute to frequency transfer between ground and space
  - Towards *Application 4* (general relativity and fundamental physics)



- Australia's first optical ground station (TeraNet-1)



- DLR's COMPASSO Mission hardware

Thanks for your attention!

- Relevant UWA Publications

[1] Dix-Matthews, et al. *Optics Express* **31** (2023) 15075

[2] Dix-Matthews, et al *Physical Review Applied* **19** (2023) 054018.

[3] Gozzard, et al. *Review Letters* **128** (2022) 020801.

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[6] Dix-Matthews, et al. *Nature Communications* **12** (2021) 515.

[7] Walsh, et al. *Scientific Reports* **12** (2022) 18345.