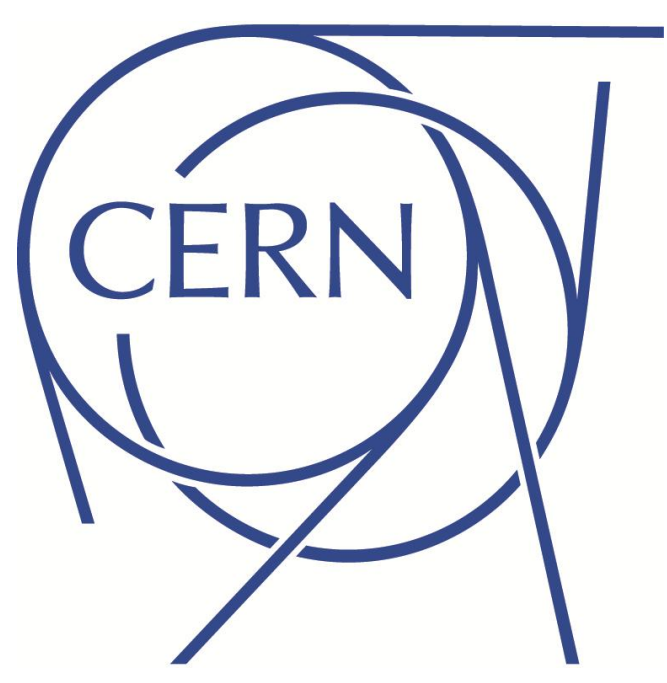




Mitigating Atmospheric Angular Refraction using Dual-Wavelength Pseudo-Nondiffracting Beams: Addressing the Engineering Challenges



M. Dušek^{1,*}, F. Barcet^{1,2}, P. Ray¹, J. Venc^{1,3}, A. Frausti^{1,4}, D. Mergelkuhl¹, J-Ch. Gayde¹

¹CERN, Geneva, Switzerland; ²ETH Zurich, Zurich, Switzerland; ³Charles University, Prague, Czech Republic; ⁴ESGT, Le Mans, France

*martin.dusek@cern.ch

CONTEXT & MOTIVATION

- **The Problem:** Straight-line optical alignment systems based on **Structured Laser Beams (SLBs)** suffer from **atmospheric refraction in open air**, where changes in temperature, humidity, pressure, and CO₂ concentration create refractive index gradients and turbulence that cause the beam to deviate from a straight trajectory.
- **The Traditional Solution:** Propagating the SLB inside a **vacuum pipe** eliminates refraction, however, this **introduces operational constraints** over long distances.
- **The Goal:** Actively **compensate for angular refraction** in free air using **dual-wavelength dispersometry**, recovering true straight-line trajectory without permanent vacuum installation.
- **Presented Research:** Evaluation of the current system performance to pinpoint key modifications for the further development, optimization, as well as providing a proof-of-concept.

DISPERSOMETRY

- **Air is a dispersive medium**, in which light bends at different rates depending on its wavelength.
- The dispersion angle $\Delta\beta$ directly relates to the refraction angle β_1 of the primary reference wavelength via the atmospheric dispersion factor K :

$$\beta_1 = K(\lambda_1, \lambda_2) \cdot \Delta\beta \quad \text{where} \quad K = \frac{n(\lambda_1) - 1}{n(\lambda_1) - n(\lambda_2)}$$

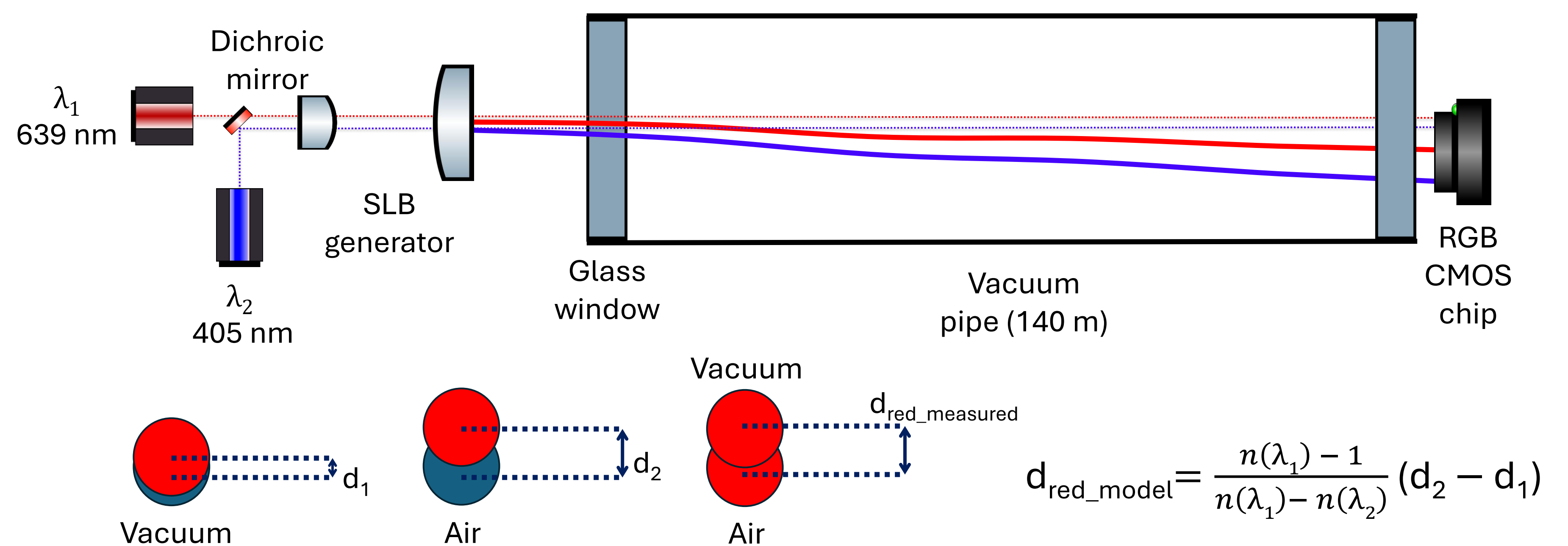
- For $\lambda_1 = 405 \text{ nm}$ (blue) and $\lambda_2 = 639 \text{ nm}$ (red), which were used in the presented experiments, $K \approx 46.4$.
- **Key Challenge:** Because $K \approx 46.4$, any baseline drift or centroid measurement error of $1 \mu\text{m}$ produces a $46.4 \mu\text{m}$ error in the corrected trajectory.

METHODOLOGY AND RESULTS

- The sensor's spectral response allowed to analyze position of both SLBs using red and blue channels with negligible crosstalk.

Measurement:

1. Beam positions recorded in vacuum ($\sim 10^{-2}$ mbar) and in air to measure $d_{\text{red_measured}}$, d_2 , and d_1
2. The measured $d_{\text{red_measured}}$ was compared to the calculated $d_{\text{red_model}}$



Parameter [μm]	Day 1	Day 2	Day 3
d_{red}	3405.5 ± 16.9	3586.5 ± 17.4	3342.5 ± 19.1
d_{blue}	3479.8 ± 19.4	3665.5 ± 19.9	3415.6 ± 17.1
d_1	652.7 ± 6.9	818.0 ± 9.4	759.4 ± 5.3
d_2	726.9 ± 5.9	738.9 ± 7.6	832.6 ± 11.1
$d_2 - d_1$	74.2	79.1	73.2
$K\text{-factor}$	46.3	46.4	46.4
$d_{\text{red_model}}$	3436.2	3671.8	3392.8
$d_{\text{red_measured}}$	3442.7	3626.0	3379.0
$ d_{\text{red_measured}} - d_{\text{red_model}} $	6.5	45.8	13.8

Vertical axis

Parameter [μm]	Day 1	Day 2	Day 3
d_{red}	154.7 ± 16.4	23.2 ± 18.9	28.3 ± 17.4
d_{blue}	125.9 ± 19.0	53.3 ± 18.9	74.0 ± 19.9
d_1	636.4 ± 7.0	706.1 ± 4.8	711.4 ± 9.4
d_2	665.2 ± 5.9	676.1 ± 7.5	757.1 ± 7.6
$d_2 - d_1$	28.8	30.0	45.7
$K\text{-factor}$	46.3	46.4	46.4
$d_{\text{red_model}}$	1333.7	1392.6	2118.2
$d_{\text{red_measured}}$	140.3	38.3	51.1
$ d_{\text{red_measured}} - d_{\text{red_model}} $	1193.4	1354.3	2067.1

Horizontal axis

Parameter [μm]	Vertical	Horizontal
d_{red}	3497.3 ± 16.8	95.9 ± 18.5
d_{blue}	3567.2 ± 19.9	97.3 ± 21.4
d_1	366.5 ± 5.4	18.9 ± 13.0
d_2	296.6 ± 6.1	17.5 ± 8.6
$d_2 - d_1$	69.9	1.4
$K\text{-factor}$	46.4	46.4
$d_{\text{red_model}}$	3244.1	65.0
$d_{\text{red_measured}}$	3532.3	96.6
$ d_{\text{red_measured}} - d_{\text{red_model}} $	288.2	31.6

Realigned

CONCLUSION AND DISCUSSION

- **Vertical Axis:** Compensating **98.7 – 99.8%** of vertical refraction with repeatable results.
- **Horizontal Axis:** Poor compensation.
- **Reproducibility:** Reducing vertical compensation to **91.8%** while horizontal compensation reached **67.3%**. The system is not yet reproducible due to high sensitivity to optical window flexure, laser pointing jitter, localized environmental sensing, and K-factor noise magnification.

Next Steps:

- **Lasers:** Launch both lasers from a single-mode optical fiber and decrease the K-factor by changing the wavelengths.
- **Cameras:** Position cameras inside the vacuum to decouple optical window flexure from measurements.
- **Monitoring:** Continuous monitoring of the environmental conditions.
- **Validation:** Validate the performance against Wire Positioning Systems and Hydrostatic Leveling Systems.