SAFS: High-Speed Density-Gradient Imaging

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Introduction

Schlieren imaging visualizes **refractive-index (air-density) gradients** by converting small light deflections into brightness changes on a camera. **Self-Aligning Focusing Schlieren (SAFS)** is designed to make this process more practical in compact setups by improving alignment repeatability while still allowing sensitivity control using a **Ronchi ruling** background and a **cutoff grid**. A common challenge in student-lab schlieren work is that small mechanical drift can make alignment difficult to reproduce and that some transient events may produce gradients that fall **below the system's detection threshold** depending on illumination, exposure, and cutoff tuning. Another practical issue is that raw **16-bit TIFFs** often look fine in the capture viewer but appear dark in other viewers unless contrast scaling is applied consistently. **Purpose:** characterize a compact SAFS system and determine what density-gradient events it can visualize reliably. **Research question:** can a student-lab SAFS setup achieve repeatable alignment and sufficient sensitivity to visualize gradients from a **round jet** and **balloon-rupture trials** using high-speed imaging?

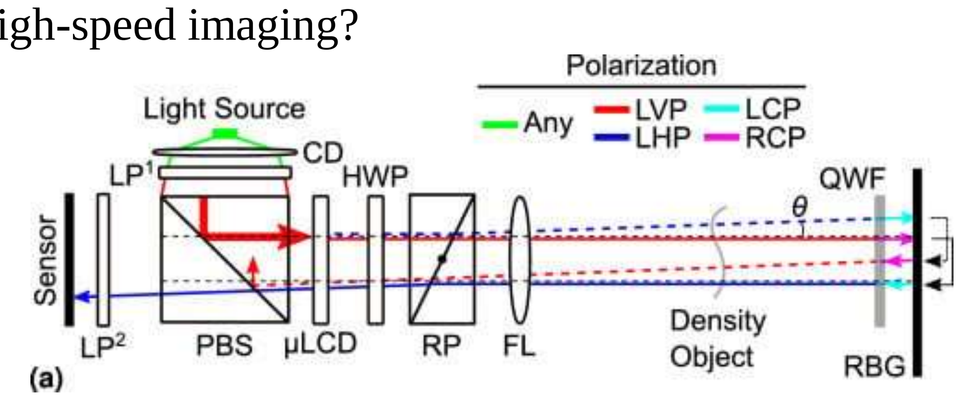

Fig I. *SAFS Setup Diagram I*

Methods

The study subject is the Self-Aligning Focusing Schlieren (SAFS) optical system and controlled test events, including a round air jet and balloon-rupture trials intended to generate a shock-like density disturbance. As shown in **Fig. 3**, SAFS uses a focusing schlieren configuration in which field lenses image the test section onto a Ronchi ruling background pattern. Light passing through the flow is refracted by density gradients, causing small deflections that shift the background pattern relative to a conjugate cutoff grid. This converts refractive-index gradients in the flow into measurable intensity variations in the final image while suppressing out-of-plane disturbances. The system uses interchangeable lenses (80 mm, 135 mm, and 200 mm) to adjust field of view and sensitivity, allowing different tradeoffs between spatial coverage and gradient resolution. A PCO high-speed camera records transient events using microsecond-scale exposures. MATLAB modeling was used to estimate depth-of-field and field-of-view characteristics for each lens configuration and guide selection of operating conditions during testing.

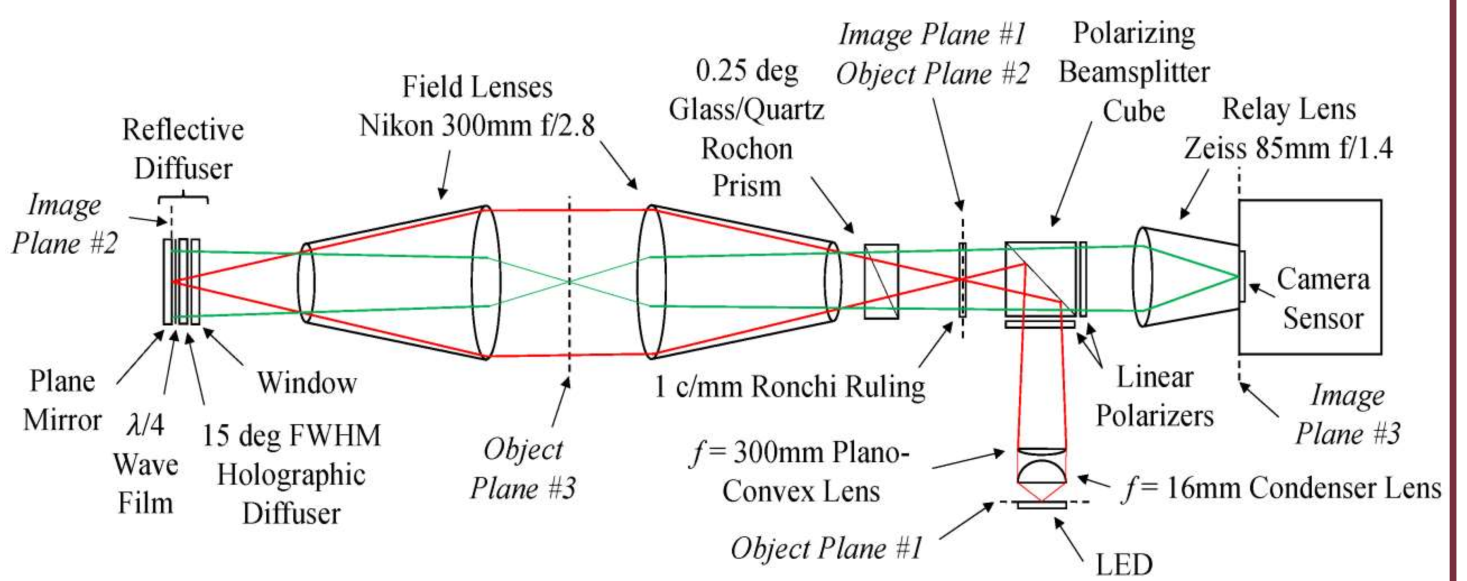

Fig. 3 *SAFS Setup Diagram 2*

Results — Jet Trials

The SAFS system produced **stable imaging** and **repeatable alignment** across runs, enabling consistent data collection. Jet trials were used as the primary test case to evaluate **field-of-view**, **image quality**, and whether density-gradient features were detectable under different lens configurations. Compared across the 80 mm, 135 mm, and 200 mm lenses, the configuration selection reflected the expected tradeoff between **coverage** (larger view) and **sensitivity** (stronger gradient visibility). Jet imaging provided the clearest benchmark for system performance and was used to verify that the system configuration and processing pipeline were functioning as intended.

Fig 4. *Balloon Pop Visualized*

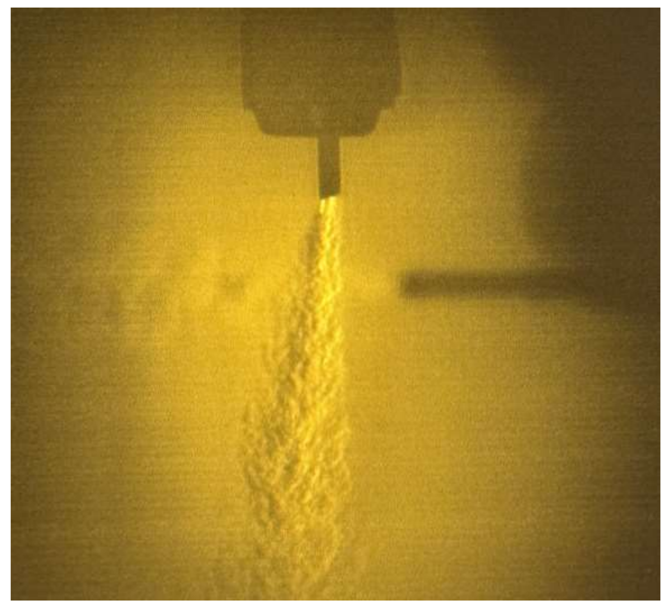

Fig 5. *Dual-Jet DOF Test*

Depth of Focus vs. Focal Length

To guide lens selection for the SAFS setup, I used MATLAB to model how **depth of focus** changes with **focal length** across the 80 mm, 135 mm, and 200 mm lenses. The depth-of-focus vs. focal-length graph shows the practical tradeoff between maintaining a usable focus range through the test section and choosing a focal length that supports the desired field-of-view and sensitivity. This comparison was used to justify which lens configuration was most appropriate for the jet and balloon trials and to set expectations for how tolerant each setup would be to small changes in alignment or test-section position.

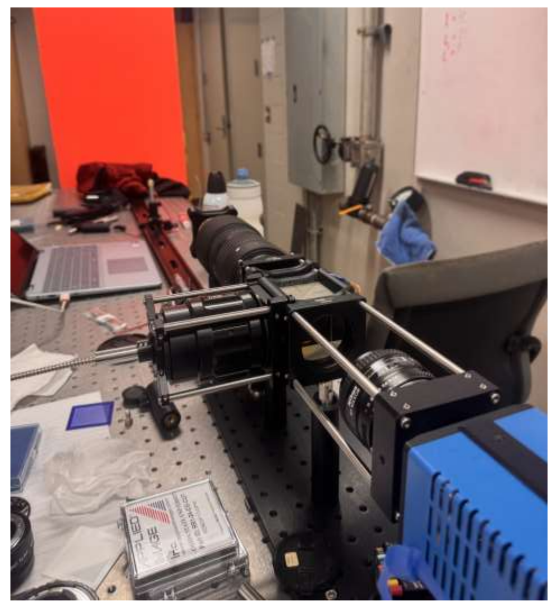

Fig 2. *FCAAP SAFS SETUP*

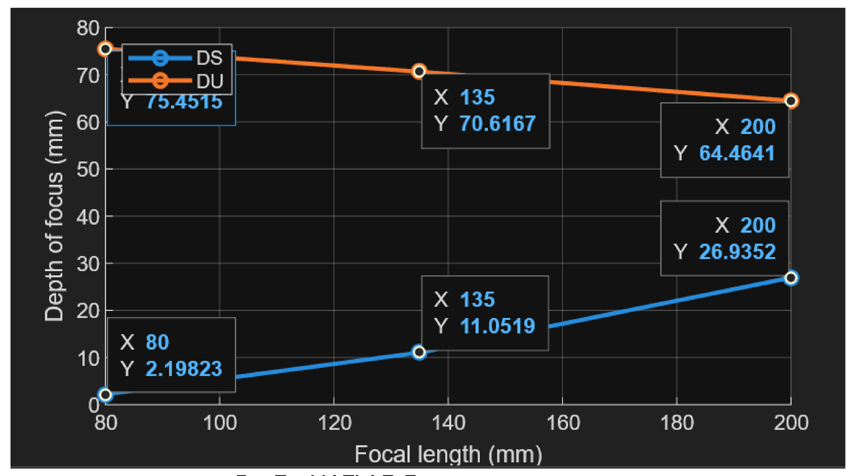

Fig 7. *MATLAB Output*

References

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Bathel, B. F., and Weisberger, J. M., "Compact, Self-Aligned Focusing Schlieren System," Optics Letters, Vol. 46, No. 14, 15 July 2021, pp. 3328–3331, doi:10.1364/OL.428011.

Conclusions and Significance

Overall, the SAFS setup demonstrated that a compact, student-lab focusing schlieren system can achieve repeatable alignment and stable imaging suitable for ongoing experimentation. While the system is functional and consistent, the balloon trials show that resolving weaker transient features requires improved sensitivity, which depends strongly on illumination, cutoff tuning, and timing.

This project demonstrates a practical pathway for **repeatable schlieren-style imaging** in a student laboratory using a compact SAFS configuration. A repeatable system reduces setup time, improves consistency between runs, and enables undergraduate researchers to collect comparable datasets over multiple sessions. The project also establishes a reproducible image-processing workflow that prevents common high-bit-depth visualization failures and supports cleaner viewing of results.

Strengths and Limitations

Strengths: The SAFS configuration enabled **repeatable alignment** and stable imaging across runs. The MATLAB-based lens evaluation supported intentional configuration selection, and the processing pipeline produced **consistent outputs across viewers**. **Limitations:** The current configuration did not resolve the balloon shock-like feature, indicating the setup's **sensitivity is not yet sufficient** for that event under present illumination/cutoff/exposure conditions. Results are **preliminary**, and quantitative sensitivity/resolution metrics are still in progress.

Next Steps and Future Work

Future work will focus on increasing sensitivity and making performance measurable and comparable across configurations. Planned steps include optimizing **illumination intensity and uniformity**, adjusting **cutoff strength and alignment** to improve gradient selectivity, and improving **trigger timing** to capture the earliest stage of transient events. The system will be characterized more quantitatively by measuring sensitivity and spatial resolution versus **lens focal length** and **grid frequency**, and the processing workflow will be automated for batch analysis and standardized for replication.

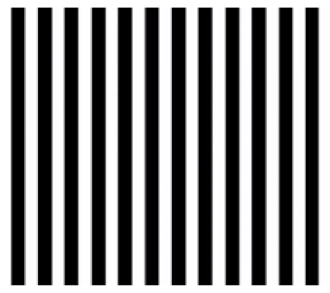

Fig 8. *Ronchi Ruling*

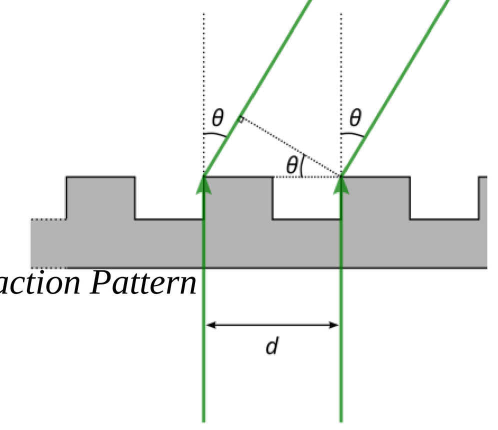

Fig 9. Diffraction Pattern

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