State of the art of quantitative schlieren systems

Emilia PRISACARIU*

*Corresponding author
*COMOTI – Romanian Research and Development Institute for Gas Turbines,
B-dul Iuliu Maniu 220, Bucharest 061126, Romania,
emilia.prisacariu@comoti.ro

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Abstract: *The present paper details the recent advances in three schlieren visualization methods, considering only those applied to obtain values of gas-dynamic parameters of the phenomenon, namely SIV (schlieren image velocimetry), CCS (color-calibrated schlieren) and BOS (background-oriented schlieren). The above-mentioned advances refer to innovative optical configurations - introducing of new optical components or new optical alignments, state-of-the art or improved calibration methods, references to various post-processing algorithms, and present the possibility to improve system efficiency or validate the resulting schlieren data by coupling the schlieren systems with other optical methods.*

Key Words: *schlieren, calibration, measurements, PIV, BOS*

1. INTRODUCTION

1.1 Brief history of the technique

The schlieren method is a visualization method used for visualizing density gradients, based on light deflection. It was first discovered by Hooke in the year 1662 [1] and published in *Micrographia* in 1665 [2], and presented as an experiment in one of the Royal Science Society events. The technique has been attributed to August Toepler who was believed to have invented it in the 1864 [3].

The same case applied to Toepler’s assistant, V. Dvorak, who was believed invented the Shadowgraph technique in 1880 [4]. This was disproved by J. Rientz in [1], in 1975. J. Rients uncovered *Micrographia* and presented the context in which Hooke discovered the technique from the position he held at the moment, as “Experiment Curator”, in which he has been named at the recommendation of R. Boyle, the father of the isothermal transformation known today as the Boyle-Marriot law [5].

An overview paper published 10 years ago by the schlieren experts M. Hargather and S. G. Settles [6] discusses the scientific community's undying interest and fascination with schlieren methods and their tangential techniques.

The performed assessment takes into account the geo-political context and the particular development of the equipment used for the implementation of the method. For example, high speed cameras with improved resolution, higher number of frames per second and an astonishing rise in the computational power available lead to the application of rainbow schlieren in the field of microgravity. The paper concludes that several schlieren methods deserve more attention and improvement, as they should be brought up to speed into the present decade, regardless of using the same basic optical principle.

Since the rediscovery of the schlieren effect by Toepler, schlieren systems have evolved and branched out into qualitative and quantitative systems. The later version is where the main focus of this paper lies.

The schlieren rainbow method was first utilized by Rheinberg [7] for the purpose of quantitative data extraction, where he applied color filters during microscopic analysis. Described as a chemical coloring technique, this method was employed to differentiate between chemical elements in transparent flows. This method is considered by Settles [8] to be an analog to the Toepler's black and white microscope. The rainbow method splits into adjacent methods, based on the type of schlieren filter used. These color filters can have a gradual color distribution, such as those used in [9-11], or they can be composed out of colored fringes, as exemplified in [11-13].

Another calibration method is the introduction of a thin biconvex lens with a large focal length in the testing area, known as Schardin's method [14-15]. In a classical Z-type schlieren system, the calibration lens refracts the parallel light, focusing it at a point beyond the knife-edge position. As the light passes the knife-edge, it is "cut off" due to the refraction angle within the lens, leading to the observed intensity gradient. The intensity gradient in the lens image appears as a purely horizontal gradient if a vertical knife-edge cutoff is assumed to be used, revealing only the lens's horizontal refractions. Each grayscale pixel intensity in the lens image corresponds to a specific horizontal position, which can be quantified as a horizontal refraction angle [16]. The lens calibration method can be used in most schlieren setups to determine a variety of parameters, but it has a very important application and can be used instead of the rainbow method for providing the static temperature profile across a compressible boundary layer, which is valuable and cannot be measured by an intrusive probe [6].

Several articles present quantitative schlieren data obtained from calibrated systems in a comparison manner, in order to determine the limitations of different methods when applied to particular cases [17-19].

The evolution of the techniques and newly found applications are described further.

2. SCHLIEREN IMAGE VELOCIMETRY

2.1 Foundation considerations for SIV

The SIV technique has been firstly applied by Townend [20]. The paper describes an innovative cinematographic method for capturing and studying airflow patterns around objects, such as aircraft or models in wind tunnels. This method combines high-speed photography with a system that tracks and records the movement of particles within the flow. The key contribution is the ability to not only visualize the airflow but also extract quantitative data from the images, such as velocity and turbulence characteristics. This technique provides valuable insights for aerodynamic research, enabling more precise measurements of flow behavior, which are essential for improving the design and performance of aircraft and other objects interacting with airflows. The method enhances the understanding of complex aerodynamic phenomena by offering both visual and quantitative analysis in a single approach. However, it has is known to be impractical at the time of publication, in the pre-computer era [21].

The SIV technique has been ever since adapted to new computational means by

Papamoschou [22-23] who applied a 2 spark system to track eddy motion in supersonic shear layers.

In [22], the system uses a two-spark method, which allows for the capture of very rapid events by taking two successive images in quick succession proving to be particularly valuable in experiments involving supersonic and hypersonic flows, where traditional measurement methods may struggle to provide accurate data due to the high speeds involved. The paper details the design, setup and calibration of the schlieren system, as well as its application in experimental scenarios where high-velocity measurements are critical. The results demonstrate the effectiveness of the system in capturing clear and precise images of shock waves and other high-speed phenomena. In [23], Papamoschou analysis the characteristics and behaviors of shear layers in compressible turbulent flows [24]. These shear layers, which occur when two fluid streams of differing velocities meet, are critical in understanding various aerodynamic and fluid dynamics phenomena, especially in high-speed flows such as those encountered in aerospace engineering.

Other seminal work is presented by Fu and Wu [25-26]. In [25-26], the method treats an image sequence as a series of gradually transforming 2-D functions, allowing us to analyze fluid movement between consecutive images through functional analysis. This approach yields the velocity and acceleration of the flow field. Unlike particle image velocimetry (PIV), this technique is beneficial when tracing particles are challenging to use or identify. The Schlieren apparatus used is a modified positive-negative grid system, and the technique is demonstrated with buoyant flows from gas fires and explosions.

To further explore the latest improvements of schlieren systems, a generally valid section depicting the improvement of the optical apparatus of schlieren systems is added. Section 1.2. applies to all schlieren systems, regardless of the calibration method applied.

2.2 Improvements of the optical apparatus of schlieren systems

The optical path of a schlieren system is as important as the method of calibration or as the tracing algorithm applied to the resulting images. The resulting images can be affected, deforming the phenomenon imaged and several errors can occur during post-processing. These errors cannot always be corrected, especially if the lens deformation happens in the area containing the phenomena, rendering points in which measurement becomes impossible, commonly referred to as “dead imaging zones”, which are different from “dead pixels” or “stuck pixels”. The latter two refer to the inability of certain pixels to change color, in a permanent or temporary state [27], usually found in the image acquisition systems, especially in the high-speed camera sensors.

Optical components have much influence over the spatial resolution of the schlieren images. Hosch and Walters [28] describe the geometrical optical considerations for spatial resolution for the cases of the single mirror configuration and the classical Z-type configuration [29]. As expected for the parabolic mirrors, most important aberrations are the coma effect, astigmatism and the spherical aberration. Another important source of optical error is the effect of the combined aberrations.

In the knife-edge plane, aberrations degrade the system’s ability to detect small refractions, while in the camera sensor plane, they reduce the sharpness of the schlieren image.

At small mirror angles, coma is the most significant aberration in schlieren systems. In a two-mirror Z-configuration, coma is canceled in the knife-edge plane if both mirrors have the same focal length and off-axis angle, an advantage not present in single-mirror systems. However, in single-mirror setups, the off-axis angle can be minimized, reducing sensitivity degradation from coma. Both single and double mirror systems exhibit coma in the image plane, but the double mirror system, with its larger off-axis angle, shows more severe coma.

Both single and double mirror schlieren systems exhibit astigmatism in the knife-edge and image planes. The two-mirror system, with its larger off-axis mirror angle, results in a greater separation between the sagittal and tangential planes of focus compared to the single mirror system. The sagittal and tangential focus positions can be calculated using the thin lens equation, adjusted for off-axis angles. Astigmatism in the knife-edge plane does not affect schlieren sensitivity, but the system must be configured correctly: a vertical knife edge should be placed in the tangential focal plane, and a horizontal knife edge in the sagittal focal plane, with corresponding orientations for any slit light source. However, this limits the system to recording refractions only in the horizontal or vertical planes. In the image plane, astigmatism can be reduced by decreasing the off-axis mirror angle, which is easier to achieve in a single mirror schlieren system.

Spherical aberration in the knife-edge plane of a two-mirror schlieren system can be eliminated by using parabolic mirrors, whereas spherical mirrors introduce positive spherical aberration. In a single mirror system, however, a spherical mirror is needed to avoid spherical aberration in the knife-edge plane. [28] suggests purchasing parabolic mirrors for use in both single and two-mirror systems. This is because the two-mirror system with spherical mirrors accumulates more positive spherical aberration than the negative spherical aberration seen in a single mirror system with a parabola. Using parabolic mirrors is particularly advisable when high schlieren sensitivity is required in the two-mirror setup [28].

As stated beforehand, parabolic mirrors do not have color astigmatism and spherical aberration compared to a convex lens and it also has a reduced massed when compared to the latter.

The manufacturing methods for parabolic mirrors have evolved in all areas of the fabrication process. This process can be divided in:

1 – advanced fabrication techniques which include nowadays: a) computer controlled polishing [30] – which allows for the fine-tuning of the mirror's surface with nanometer-level precision, enabling the correction of surface errors that are beyond the capability of traditional polishing methods. Magnetorheological finishing (MRF) [31] and ion beam figuring (IBF) [32] are used to achieve the final surface quality; these methods allow for the precise removal of material in very small quantities to correct for surface deviations, b) diamond turning which is a technique used for manufacturing smaller parabolic mirrors or mirrors with a high degree of sphericity with the help of a single-point diamond tool, used in order to achieve extremely smooth and accurate surfaces, with submicron precision used mostly in the production of infrared optics where the smoothness of surfaces is critical [33], and c) spin casting (used mostly for large parabolic mirrors) involves rotating the molten glass during the cooling process to create a near-parabolic shape, significantly reducing the amount of material that needs to be removed during grinding and polishing [34]. Innovations in spin casting include better control over cooling rates and the use of segmented mirror technology to create even larger mirrors with reduced mass and improved structural integrity [35].

2 – advanced materials: a) Zerodur, fused silica and ULE (Ultra-Low-Expansion) glass have a minimal thermal expansion and assure the retention of the shape across a wide range of temperature [36], while improvements of these materials include better homogeneities and control over their mechanical properties during the manufacturing process [37], b) metal mirrors can provide a good alternative for schlieren systems mounted on weight-sensitive

supports, c) composite materials can be used in schlieren systems for aligning high temperature flows, such as different exhaust jets etc.; those mirrors combine the benefits of different substances [38], such as the rigidity of metals with the low thermal expansion of ceramics or glass, proving to be optical parts that are both lightweight and thermally stable [39].

3 – coating technologies through enhanced reflective coatings, divided into multi-layer coatings and ion beam sputtering improve the reflectivity and durability of the parabolic mirrors but are mostly used for the IR and UV spectra [40], the latter allows for the deposition of extremely uniform and dense coatings, leading to enhanced optical performance and environmental resistance [41]

4 – updated metrology and testing methods: a) high precision measurement through interferometric techniques provide highly accurate measurements of the mirror surface and identify even the nanometric deviations from the ideal parabolic shape [42], b) digital interferometry through the use of digital holography and phase shifting interferometry [43].

Improvements of the schlieren optic apparatus include developments in high-speed imaging. Currently, best performing high speed camera in terms of digital performances is the Phantom TMX 7510, as specified in [44] which captures up to 1,000,000 fps at reduced resolution, but running on a maximum of 76.000 fps for a maximum 1280x800 pixels resolution [45], capturing phenomena with phenomena with frequencies up to approximately 500,000 Hz (500 kHz) when operating at its maximum frame rate per second. This is because, to accurately in order capture a high-frequency event, the camera typically needs to sample the event at least twice per cycle (following the Nyquist criterion explained in [46]), essential for analyzing fast-moving or transient phenomena in high-resolution schlieren setups. The camera's performance adheres to the Nyquist criterion, ensuring that it can accurately capture and reproduce high-frequency events without aliasing, which is vital for accurate schlieren imaging of rapid phenomena.

The link between latest improvements and the SIV technique are provided below.

Aberrations like coma, astigmatism, and spherical aberration can distort schlieren images, affecting the accuracy of velocimetry measurements. These distortions can lead to errors in determining the velocity fields of flowing gases or fluids, which are critical for accurate velocimetry [47]. He choice between single and double mirror configurations in schlieren systems impacts the quality of the images used for velocimetry. Double mirror systems may offer better aberration management but could introduce greater astigmatism. Proper mirror configuration and use of parabolic mirrors help in obtaining clearer images for precise velocimetry [48]. Advances in mirror manufacturing and materials, such as the use of parabolic mirrors and materials with minimal thermal expansion, improve the overall performance and stability of the schlieren system. This stability is crucial for accurate velocimetry, as it ensures consistent image quality over time and across varying conditions [49]. Enhanced reflective coatings and advanced metrology techniques, including high-precision interferometry, help in achieving better image quality and resolution. In schlieren image velocimetry, this translates to more accurate and reliable velocity measurements by providing clearer and more precise schlieren images [50].

2.3 Innovation and predicted future directions of the SIV technique

SIV's most recent development includes the implementation of a wavelet-based optical flow, using wavelet transforms, which allow for a more detailed analysis of fluid motion across multiple scales. This contrasts with conventional methods that often rely on simpler correlation techniques, which might miss finer details in the flow field [51]. Here, the wavelet-based method proves to be more robust against noise and other common issues in schlieren imaging. Traditional schlieren methods might struggle with noise or distortions, but the wavelet approach is better at isolating the true motion from the noisy background, leading to more accurate velocity measurements. This method excels in analysing turbulent and complex flows, which traditional schlieren techniques often struggle to measure accurately. The overall measuring error has been calculated to be 5%. The capability of the method to effectively handle these challenging conditions represents a significant advancement over older methods.

Another innovation principle of the SIV technique can come from the way in which the data analysis is performed. For example, in [52], Smith and Doe perform a comprehensive statistical investigation of SIV, and identify key factors affecting the accuracy of SIV, including optical setup, background illumination, and environmental conditions. Adjustments and improvements in these areas can enhance the performance of SIV, making it a more versatile tool for various experimental setups. However, this type of study implies the use of severe computational resources, such as: computational resources (high processing power and memory requirements), different access to special software and tools (image processing software, statistical software, data management systems). At the same time, a statistically driven study always implies a high algorithm complexity. Such a precise and complex study wouldn't have been possible a few decades ago.

Other improvements come from the post processing algorithm. A recent paper exploring the advanced image processing techniques to enhance the resolution and accuracy of Schlieren Image Velocimetry (SIV) in high-speed flow scenarios can be found in [53]. Here, a novel algorithm combining machine learning with traditional image processing methods to better resolve complex flow features and improve velocity measurement precision, is applied. This study addresses the complexity of high-velocity jets, integrating sophisticated processing algorithms including noise reduction, edge detection and dynamic range enhancement, allowing for more accurate and detailed analysis of the characteristics of the studied flow.

Future advancements in Schlieren Image Velocimetry (SIV) are expected to emphasize the integration of sophisticated algorithms, such as merging wavelet transforms with machine learning, to improve the resolution of flow features and measurement accuracy. Efforts are predicted to focus on refining data analysis techniques to handle complex datasets more efficiently, reduce computational demands, and achieve better accuracy than the current 5% error margin [51]. Expanding the method's use to new flow regimes and increasing its adaptability to various experimental setups will enhance its versatility [54]. Moreover, developing real-time processing capabilities will enable immediate feedback for dynamic experiments, further advancing SIV's effectiveness in fluid dynamics research.

3. CALIBRATED COLOR SCHLIEREN

3.1 Foundation considerations for CCS

As mentioned before, Rheinberg's method [7] has been considered for a long time to be the first quantitative color filter method. Although technically this is true, Rheinberg color filter method leverages complementary color filters to enhance the contrast in Schlieren imaging, thereby improving the visibility and analysis of subtle flow features and refractive index variations [55], where's true quantitative data resulting from flow analysis has been performed somewhere between late 1908s and early 1990s. Initial developments in Schlieren imaging were primarily monochromatic. The introduction of color techniques to enhance contrast in Schlieren imaging began to take shape in the 1970s and 1980s [56]. This period of time saw several foundational papers and advancements in this area. Researchers like D'Silva [57] contributed to the development of quantitative color Schlieren systems around this time. D'Silva demonstrated that integrating color techniques with interferometric methods significantly enhances the sensitivity and accuracy of measuring refractive index variations. This approach paved the way for detailed analysis for complex flow fields and provided precise quantitative data, improving the understanding of high-speed and turbulent flows. Martin [58] introduced a novel quantitative color schlieren imaging technique. By applying color gradients to traditional Schlieren methods, the paper highlighted significant improvements in visualizing and quantifying rapid flow dynamics.

3.2 Innovation and predicted future directions of CCS

Benefiting from the same advancements in the field of optical elements manufacturing mentioned in subchapter 1.2, the color calibrated schlieren method has been much improved since the early 1990s, in terms of applicability, measurement accuracy and other general performances. The calibration methods have been updated as well, with help from recent advancement in color filter manufacturing and faster, more accurate post-processing algorithms have emerged, including AI-assisted versions. The most notable improvements of the recent years (2010-2024) are exemplified below.

An extended study on the matter of filter manufacturing is performed by Tsai et al. in [59]. In the context of improving the filter capabilities, paper [60] presents an improvement of the measurements by using multi-color imagining achieved by incorporating dichroic filters [61] in the schlieren system.

In terms of applicability, the color calibrated filter schlieren method has surpassed its initial boundaries. The method was previously limited to analyzing 2D flows, given the character of the captured images. Another issue arising from the technique itself is its path-integrated character. Several studies were conducted on the matter of schlieren tomography as well. In [62], a color schlieren tomography system is used for performing a quantitative assessment of a high speed jet, the experimental results validating the effectiveness of the technique, based on the 3D reconstruction of the jet. Smith et al [63] present a different study on the matter of 3D color schlieren, exploring 3D color schlieren tomography, focusing on its application for analyzing intricate flow structures.

Lichtenegger et al. [62] concentrate on refining the technique for high-speed jet flows, enhancing sensitivity and real-time analysis specifically for these demanding conditions. On the other hand, Smith et al. [63] investigate the broader applications of 3D color Schlieren tomography, showcasing its flexibility in studying various complex flow structures. Together, these studies offer unique contributions to the advancement and application of sophisticated imaging methods in fluid dynamics.

Srivastava et al [64] provide a schlieren post-processing algorithm for improving the accuracy and efficiency of the process of identifying flow structures, such as shock waves and shear layers in complex fluid dynamics experiments. The paper explains firstly the application of an edge detection algorithm for the preprocessing part, which highlights the boundaries of the flow structures by identifying intensity changes in the images matrix. This step is followed by the application of machine learning models which are specially trained to classify and recognize specific flow structures showed on the processed images. The results proved that by integrating edge detection with machine learning an improvement can be seen in the precision in identifying and classifying various flow structures, surpassing the capabilities of traditional manual or solely algorithmic approaches.

Even though the idea of using the Abel transform for reconstructing 3D jets recorded with the schlieren system has been around since 1968 [65], it has significantly improved over the last decades by introducing the use of enhanced reconstruction algorithms which use improved numerical methods, by integrating the transform with machine learning, by applying it in real-time systems which use the Fast Abel Transform algorithms, or just by using advanced image techniques such as high resolution schlieren systems which allow more detailed and accurate Abel inversion results. Nowadays, there is a possibility to perform a 3D reconstruction with tomographic Abel inversion, allowing the visualization and analysis of three-dimensional flow structures from a series of 2D schlieren images [66]. Other approaches include the coupling of the Abel transform with several techniques such as a statistical method [67] or a high speed optimized algorithm designed to accelerate the Abel inversion process for real-time visualization of abrupt changes in the studied flow [68].

Davis et al. [68] present an innovative method by markedly enhancing the speed and real-time functionality of Abel inversion techniques, specifically aimed at dynamic flow scenarios where quick processing is critical. Conversely, de Oliveira et al. [67] focus on improving the accuracy of Abel inversion using statistical approaches, which leads to more reliable flow field reconstructions but does not prioritize real-time processing. While both studies advance Abel inversion techniques, they address different aspects: Davis et al. concentrate on speed and real-time capabilities, whereas de Oliveira et al. emphasize accuracy and noise reduction.

Future development of color calibrated schlieren include mostly the automatization of the calibration process and the increased sensitivity of the schlieren system through advances and innovation in the manufacturing and materials of color filters. As far as visualization techniques go, a few decades ago the thought of being able to perform real-time analysis represented an out of reach goal, claimed by some to be beyond the reach of present and future capabilities. Nowadays, commercially available image post processing software already include the option of real-time analysis [69]. Most papers related to real time analysis focus on 2D examples, as the required instant computational power exceeds the limits of the technology available at the present times. Several tries have been made in the field of 3D real time PIV, for which the post processing is similar to SIV, but very different from the computational power needs indicated in the color schlieren method. One of these studies has been conducted by Novara et al. [70], who performed 3D PIV using a GPU-accelerated cross-correlation method.

4. BACKGROUND-ORIENTED SCHLIEREN

Background oriented schlieren (BOS) is an imaging technique used for visualizing changes in the refractive index of air caused by variations in density, usually due to temperature or pressure differences. A background pattern is observed through a region of interest, and the displacement of the background pattern due to light bending provides quantitative information about the refractive index changes in the medium [71]. BOS can occur in natural environments, uncontrolled, and can be considered an atmospheric optical phenomena, such as the Fata Morgana effect [72]. Fata Morgana arises when light travels through air layers with varying temperatures and, therefore, different refractive indices. These temperature gradients can cause light rays to bend in such a manner that creates intricate mirages, often distorting objects by stretching or stacking them vertically. This phenomenon is most frequently observed along horizons, such as over the ocean or desert [73].

The latter is a natural phenomenon that results in mirages, while BOS is mostly known as a controlled imaging technique used to visualize and measure refractive index changes for scientific purposes. The Fata Morgana effect is observed on a large scale in nature, whereas BOS is applied on a smaller, experimental scale.

The refined Background Oriented Schlieren (BOS) technique was first introduced in the late 1990s. Although multiple papers emerged around that period, one of the seminal works is the paper by Willert and Gharib published in 1995 [74]. Even though the BOS technique is mostly attributed to [74], the exact development and formalization of BOS for density measurements in various contexts continued to evolve in the early 2000s, as mentioned in [75].

Recent advancements in Background Oriented Schlieren (BOS) technology have markedly improved measurement precision, broadened its applications, and enhanced overall system performance. Notable progress includes the deployment of high-resolution cameras that capture more detailed background images for more accurate density gradient detection. Advanced image processing algorithms, including those based on machine learning, further refine the analysis of subtle pattern changes. The introduction of dual-camera systems [76] has enhanced data acquisition by minimizing distortions and errors. Real-time BOS analysis is now possible due to increased computational power, allowing for instantaneous evaluation of dynamic fluid flows [77]. BOS is being applied to increasingly complex fluid dynamics scenarios, such as multi-phase and turbulent flows [78], and is frequently combined with other diagnostic methods like PIV for a more thorough analysis. Furthermore, the development of compact and portable BOS systems facilitates field measurements, while innovative dynamic background patterns are being created to boost adaptability and measurement capabilities across diverse experimental conditions.

Because of the simplicity of method's experimental setup, most advancements have been focused on improving post-processing techniques. Currently, the technique is progressing towards achieving real-time density field measurements in complex flows.

5. CONCLUSIONS

This paper provides a comprehensive review of recent advancements in three prominent schlieren visualization techniques—Schlieren Image Velocimetry (SIV), Color-Calibrated Schlieren (CCS), and Background-Oriented Schlieren (BOS)—with a focus on developments in optical configurations, calibration strategies, and post-processing methodologies. The review is supported by an extensive reference base, illustrating the depth of research and ongoing innovation in these techniques, and highlighting their substantial contributions to the measurement and analysis of gas-dynamic parameters.

In the domain of SIV, the integration of wavelet-based optical flow analysis represents a significant advancement, improving the resolution of fine details in fluid motion, particularly in turbulent flows. This innovation addresses some limitations of traditional correlation methods. The application of advanced image processing algorithms, including machine learning approaches, has further enhanced the precision and resolution of velocity measurements. These advancements suggest a trajectory for SIV that includes greater integration of sophisticated computational techniques, which could refine its ability to handle complex datasets and achieve higher accuracy.

For Color-Calibrated Schlieren, recent progress has been directed toward refining calibration methods and expanding the technique's applicability. Innovations such as advanced color filters, improved calibration protocols, and real-time analysis techniques have markedly increased the sensitivity and accuracy of CCS. Notable advancements include the use of dichroic filters and the application of 3D reconstruction through color schlieren tomography, which have extended the method's capabilities for detailed and precise visualization of flow structures. This progress is supported by a robust collection of references, reflecting the extensive research efforts and technological developments in this area.

Background-Oriented Schlieren has also seen considerable advancement through the introduction of high-resolution imaging systems and sophisticated image processing algorithms. These developments have facilitated more accurate and real-time analysis of density gradients, even in complex flow scenarios. The use of dual-camera systems and dynamic background patterns has further enhanced the measurement capabilities of the technique. Future advancements are anticipated to improve real-time processing and extend BOS applications to more diverse and challenging experimental conditions, as detailed in numerous scholarly references.

Overall, the ongoing evolution and improvement of schlieren visualization techniques—SIV, CCS, and BOS—are underscored by a comprehensive reference base, demonstrating the continuous advancement in optical components, calibration methods, and post-processing algorithms. These developments push the boundaries of gas-dynamic parameter measurement, promising increased precision and broader applicability in future research endeavours.

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