Volume 9, Issue 9, September – 2024 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

Investigating the Influence of Wavelength-Specific Textured Backgrounds in Background Oriented Schlieren (BOS) Imaging

Dhruv Hegde[1]; Tejash Gupta[2]; Vikram Haran[3]; Ray Shurdha[4]; William Filocamo[5]; Mason Corey[6]
[1]Salem High School, Canton, MI
[2]Fulton Science Academy Private School, Alpharetta, GA
[3]Academy of Aerospace and Engineering, Windsor, CT
[4]Bronx High School of Science, Bronx, NY
[5]Regis High School, Manhattan, NY
[6]Kingsway Regional High School, Swedesboro, NJ

Abstract:- This study investigates the influence of wavelength-specific textured backgrounds on the effectiveness of Background-Oriented Schlieren (BOS) imaging, focusing on wavelengths from 400 nm to 670 nm at intervals of 30 nm intervals and multiple captured recordings for each background wavelength interval. By analyzing the signal-to-noise ratio (SNR) computationally, and the image gradient magnitude, we aimed to determine the optimal wavelengths for capturing turbulence and determine the effectiveness of colored backgrounds in natural external environments for schlieren. The SNR, calculating the ratio of mean signal intensity to noise standard deviation, revealed the highest value at 550 nm (SNR = 22.8), indicating maximized clarity. Similarly, image gradient magnitude, computed using the Sobel operator to assess spatial intensity changes, peaked at 550 nm (G=52.3), confirming effective turbulence visualization. Our findings align with the Bayer color filter trend, suggesting that the green spectrum is particularly advantageous for BOS imaging. Deviations at 490 nm and 580 nm, characterized by lower SNR and gradient magnitude, could be attributed to atmospheric scattering, refractive index overlap, or slight digital video capture differences., highlighting environmental factors that can influence imaging performance and value variation. These insights emphasize the importance of wavelength selection and background design in real-world BOS applications, suggesting that while 550 nm provides optimal results, further refinement may enhance the effectiveness of other wavelengths.

I. INTRODUCTION

A. Schlieren Imaging and Background Oriented Schlieren (BOS) Imaging

Schlieren Imaging has been a foundational imaging method in fluid dynamics since its initial development in the 19th century, when it was introduced to study supersonic flows and shock waves in a precise manner. The method leverages the principle of light refraction, where light passing through a medium with varying refractive indices bends according to the density variations within the medium itself. These variations are often caused by the differences in temperature, pressure, or composition in gasses or liquids. Traditional Schlieren systems consist of a point light source, a set of lenses or mirrors to collimate and focus the light, and a knife-edge or filter positioned at the focal point. When the refracted light reaches the particular knife-edge, it blocks the traveling of light to a given extent, resulting in variations in intensity that correspond to the refractive index changes in the medium itself. Being a purely optical method of visualization, Schlieren imaging is unintrusive giving it the capability of imaging sensitive phase objects without unintentionally manipulating the target airflow. Schlieren imaging is highly sensitive to changes in camera movements meaning precise imaging setups are required to accurately image airflow and particle velocity [1].

The sensitivity of Schlieren imaging to minute variations in refractive index makes it an invaluable tool in aerodynamics and fluid mechanics. Refractive index variations are induced by changes in the density of the medium, which in turn are often caused by temperature gradients, pressure fluctuations, or the presence of shock waves. The degree of light deflection in Schlieren imaging is governed by Snell's Law, which relates the angle of incidence to the angle of refraction, contingent on the refractive indices of the media involved. The resulting Schlieren images are essentially shadowgraphs that reveal the spatial distribution of these refractive index gradients [2]. However, traditional Schlieren imaging systems are inherently complex and require meticulous alignment and calibration. They are also sensitive to mechanical vibrations and air currents, which can introduce noise into the system, reducing the clarity and accuracy of the resulting images. This limitation has driven the development of alternative techniques that retain the diagnostic power of Schlieren imaging while offering greater flexibility and ease of use.

Background Oriented Schlieren (BOS) imaging is an optical technique built upon the principles of Schlieren Imaging used to visualize and quantify refractive index variations induced by density gradients within transparent media, such as air. BOS imaging is founded upon the principles of traditional Schlieren photography but diverges

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

from the foundational knife-edge principle by using a textured background. This difference enhances adaptability to diverse experimental conditions and improves imaging efficiency. The core mechanism of BOS imaging involves capturing the apparent displacement of background features as light moves through regions of varying refractive index caused by changing gradients within the air. Unlike traditional Schlieren imaging, BOS is a visualization technique capable of measuring and displaying the displacement of transparent media by comparing the distorted images caused by the flow field changes with the undistorted image. BOS has the inherent ability for a greater range of applications, not necessarily needing any complex setups, often conducted using natural backgrounds. This process is widely used in fluid dynamics to measure the velocity of flow fields and refractive index gradients. For more controlled testing, BOS imaging is done on a textured plot background which is superimposed on an incoherent white light source. The displaced background features, taken in small groups of pixels, are typically compared using cross-correlation for particle imaging velocimetry. Once the matching set of pixels is located, their relative positions define a 2D displacement vector which represents the refraction of light caused by the change in refractive index within the flow [3].

The mathematical foundation of BOS involves solving for the displacement field between the distorted and reference images. This is typically achieved using cross-correlation techniques, where small windows of pixels from the distorted image are matched with corresponding regions in the reference image. The displacement vector for each pixel window provides a direct measure of the refractive index gradient. The resulting displacement field can be further analyzed to extract quantitative information about the flow field, such as velocity vectors or density gradients [1][4]. BOS imaging offers several advantages over traditional Schlieren imaging. It is less sensitive to mechanical vibrations and does not require precise optical alignment, making it more adaptable to a wide range of experimental setups. Additionally, it is more versatile in application and does not need as specific a setup to provide a formulated output to visualize airflow; natural backgrounds can serve as the patterned backgrounds, so simple fluid fields can be images in their existing state using this technique.

One of the critical considerations in BOS imaging is the choice of background pattern. The pattern must be sufficiently random to allow for accurate cross-correlation but also high-contrast to ensure that the displacement of background features is detectable. Synthetic patterns, such as grids, checkerboards, or speckle fields, are often used in controlled laboratory environments to maximize the precision of measurements. These patterns are typically printed on a flat surface and illuminated uniformly to provide a consistent background for imaging. In contrast, natural backgrounds offer the advantage of not requiring any additional equipment but may introduce variability in lighting conditions and pattern characteristics. The resolution and sensitivity of BOS imaging are directly related to the quality of the background pattern and the imaging system's resolution. High-resolution cameras and lenses with minimal distortion are essential for capturing fine details in the displacement field. Moreover, the spatial resolution of the displacement measurements is determined by the size of the pixel windows used in the cross-correlation process. Smaller windows offer higher spatial resolution but may reduce the accuracy of the correlation, especially in regions with low contrast or noise [5].

Within this study, we aim to collect data to factor in the consideration of the wavelength perpetuating the background within the imaged flow field. The wavelength of light could play a critical role in the interaction between the refractive index variations and the observed background, potentially altering the visibility and clarity of the Schlieren effect. Different wavelengths of light have varying degrees of penetration and scattering within the medium, which can enhance or diminish the displacement of background features. For instance, shorter wavelengths, such as blue or violet light, may provide higher resolution and sensitivity to minute refractive index changes due to their shorter wavelength and higher energy [6]. On the other hand, longer wavelengths, like red or infrared light, might be more suitable for detecting larger-scale density gradients or flows involving specific gasses that have particular absorption characteristics. By systematically studying the effect of different wavelengths on BOS imaging, this research aims to identify optimal background colors for specific applications, thereby improving the adaptability and precision of BOS techniques across various experimental and environmental conditions. This approach could lead to the development of more tailored BOS systems that are fine-tuned for specific diagnostic tasks, whether in fluid dynamics, combustion studies, or environmental monitoring [7].

B. Electromagnetic Spectrum and Wavelengths

In BOS a field of interest is the optimization of light wavelengths on a textured background. Currently, visible light is commonly used due to its availability and the fact that visible light is standard for most imaging equipment. Measured wavelengths commonly measured in BOS imaging include anywhere from 495 nm to 750 nm. This range of wavelengths corresponds to the visible spectrum of light. In BOS imaging, the interaction between light and matter is leveraged to detect variations within the refractive index of a particular medium, typically caused by changes in density or temperature gradients [8]. Each wavelength within the visible spectrum interacts with matter differently, affecting the refractive index and, consequently, the displacement of background features in a BOS setup.

In the context of our study within BOS imaging, we focused on the aforementioned visible spectrum range as it corresponds with the Bayer spectrum for transmission and can account for the widest range of possible backgrounds and optical sensors used to measure said backgrounds. The refractive index, which is a function of the wavelength, governs how light propagates through a medium. The refractive index determines the phase velocity of light in a medium and varies with wavelength, which is essentially the phenomenon of dispersion [9]. Dispersion causes different wavelengths to refract through varying degrees, influencing the apparent displacement of the background features

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

captured in BOS imaging. Shorter wavelengths such as violet (380-450 nm) and blue (450-495 nm), exhibit stronger scattering due to their higher energy and shorter wavefronts. This scattering lies under the Rayleigh process, which scales with λ^{-4}, meaning that shorter wavelengths scatter significantly more than longer wavelengths, such as red (620-750 nm). This scattering effect is particularly pronounced in media with small particles or inhomogeneities, where the interaction between light and matter is strong enough to cause measurable refraction [10].

The sensitivity of BOS imaging to particular wavelengths can be enhanced by employing narrow-band filters or monochrome cameras that are tuned to specific wavelengths. For instance, when using a monochrome camera with a narrow-band filter centered at a particular wavelength, the system can become more responsive to refractive index changes at that wavelength. This technique is particularly effective in experiments where the medium under investigation has a wavelength-dependent refractive index, such as in gas flows with specific absorption features. The use of monochrome cameras can also mitigate the effects of chromatic aberration, where different wavelengths focus at different points, thus preserving the fidelity of the BOS measurements.

The refractive index of gasses, is described by the Gladstone-Dale relation, $n(\lambda) - 1 = K(\lambda) \cdot \rho$ where $K(\lambda)$ is the Gladstone-Dale constant and ρ is the density, which varies with wavelength. This relationship underscores the importance of wavelength selection in BOS imaging, as different gasses will exhibit different refractive indices at different wavelengths [11]. For example, imaging a flow containing gasses like nitrogen dioxide (NO_2), which has significant absorption in the green region (495-570 nm), can benefit from using green light to enhance contrast in the BOS images.

The interaction between different wavelengths and optical sensors is critical in BOS imaging. The spectral response of a sensor, which describes its sensitivity to various wavelengths, plays a pivotal role in determining image clarity and contrast. Common sensors, such as Complementary Metal-Oxide-Semiconductor (CMOS) and Charge-Coupled Device (CCD) sensors, typically have peak sensitivity in the green region of the spectrum. This is largely due to the design of the Bayer filter array, a color filter pattern used in most digital cameras, which allocates 50% of its filters to green to align with human visual sensitivity. This design choice enhances the sensor's ability to capture detail in the green region but can lead to reduced sensitivity and resolution in the red and blue regions, which occupy the remaining 50% of the filter array [12].

The Bayer pattern, a mosaic of red, green, and blue filters used in most digital image sensors, is a crucial factor in how different wavelengths are captured. In this pattern, green filters are twice as prevalent as red and blue filters, reflecting the human eye's greater sensitivity to green. While this configuration is ideal for general-purpose imaging, it can be limited in BOS imaging, where precise color information is necessary for accurate displacement measurements. The interpolation algorithms used to reconstruct color images from Bayer-patterned sensors can introduce artifacts, particularly in high-contrast or fine-detail regions, which are common in BOS images. These artifacts, such as color moiré or false color, can obscure small-scale refractive index variations, leading to potential inaccuracies in flow visualization. Furthermore, the reduced resolution in the blue and red channels, due to the lower number of corresponding filters, can hinder the detection of refractive index gradients at these wavelengths, necessitating the use of specialized sensors or alternative imaging techniques [13].

C. Optical Analysis Configurations for BOS

The superimposed BOS backgrounds are traditionally black and white to visualize refractive index changes caused by disturbances. However, optimizing these backgrounds for specific wavelengths of light can significantly enhance imaging quality, offering improved viability against the illuminated background and the flow median. Different wavelengths interact with the atmosphere and various gasses in unique ways, which can be leveraged to achieve better contrast and detail in BOS imaging.

Blue light, with its short wavelength, provides high spatial resolution, making it particularly effective for detecting minute disturbances. At sea level, where the atmosphere is denser, blue light encounters increased scattering and absorption by atmospheric particles and gasses such as water vapor. Despite this, its ability to capture fine-scale disturbances remains valuable. At higher altitudes, such as in the stratosphere or mesosphere, where the air density is lower, blue light experiences less scattering, potentially offering clearer images of detailed flow structures and turbulence. For instance, blue light could be used to visualize intricate shock structures and small-scale turbulence in laboratory experiments or high-altitude observations. In contrast, green light excels in highlighting changes in the refractive index due to its interaction with specific gasses. Nitrogen dioxide (NO_2) and chlorine (Cl_2) exhibit significant absorption in the green spectrum, making green light effective for visualizing flows involving these gasses. At sea level, where NO_2 concentrations can be higher, green light can reveal detailed pollution patterns and specific gas flows. In contrast, green light is less absorbed by oxygen (O_2), providing enhanced contrast when distinguishing between different gasses. At higher altitudes, where NO_2 concentrations decrease and atmospheric density is lower, a green light may be less effective in contrast but still useful for general imaging of gas flows. Lastly, red light is less scattered and absorbed compared to blue and green light, making it suitable for imaging over longer distances and in environments with higher particulate matter. At sea level, red light can effectively highlight large-scale flow patterns and distinguish between major gasses like O_2 and CO_2 due to minimal absorption by these gasses. At higher elevations, red light can help visualize broader atmospheric phenomena such as jet streams or large turbulence patterns. Red light's utility in capturing large-scale features becomes more pronounced in the thinner atmosphere of high altitudes [14].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

At sea level, the Earth's atmosphere is composed of approximately 78% nitrogen (N_2), 21% oxygen (O_2), 0.93% argon (Ar), and trace amounts of gasses such as carbon dioxide (CO_2) (about 0.04%), methane (CH_4), and water vapor (H_2O). The density of the atmosphere and the concentration of these gasses influence how different wavelengths interact with the medium. So, as higher elevations are being considered for imaging, especially with supersonic and hypersonic phase objects existing in the form of jets that fly within either the troposphere or stratosphere. The density decreases with altitude, affecting light scattering and absorption. In this layer, the atmosphere becomes less dense, and the effects of gasses like water vapor become more pronounced in influencing the light interaction. The presence of ozone (O_3) becomes significant, especially in the ozone layer (15-35 km), which absorbs UV light. This absorption affects the visibility of certain wavelengths and can enhance imaging of specific features using UV light and colors with lower wavelengths.

In supersonic and hypersonic flows, the interaction with the surrounding medium becomes critical. At sea level, the higher atmospheric density amplifies shock waves and boundary layers, making it challenging to capture fine details due to increased turbulence and density variations. BOS imaging with blue light is particularly useful here for visualizing detailed shock structures and flow disturbances. At higher altitudes, where the atmosphere is less dense, supersonic and hypersonic flows might show less pronounced shock waves but become more challenging to image due to reduced contrast. Multi-spectral imaging, combining blue, green, and red wavelengths, can enhance overall imaging quality by leveraging the unique properties of each wavelength, but leveraging some colors within the visible color spectrum to a greater extent can help to bring about more prominent results with the processed output [15].

D. Wavelength Effects on Optical Sensors

Wavelengths have a profound impact on how optical sensors perceive data, this can affect all steps of the imaging process from image clarity to the amount of usable data. Altering the wavelength slightly can affect the sensor and the imaging process in many ways, affecting factors such as dynamic range, noise levels, and the resolution of frames. Key concepts that are responsible for the interaction between differentiating wavelengths and optical sensors are spectral response and quantum efficiency; they determine how efficiently an optical sensor can detect light across the spectrum. Spectral response refers to a sensor's sensitivity to various wavelengths of light. Commonly used sensors such as CMOS and CCD are more sensitive to green light (495-570 nm), this is because of the predominant amount of green filters in Bayer patterns. Camera company Kodak developed Bayer patterns, a technique where an array of RGB filters is placed over the camera filter. This reduces the bytes per pixel to one 8-bit byte. The pattern is then repeated over the picture in a fixed grid, one downside to this approach is the reduced resolution of the produced image. This reduced resolution can be overcome by using interpolation algorithms, which use neighboring pixels to recover lost detail. However, these algorithms can be computationally intensive, so they are used sparingly [16].

Foveon sensors on the other hand use a different approach to capturing color information. They measure the intensity of the light at each pixel and store the result in three separate channels - red, green, and blue. This allows them to capture more information in each pixel, resulting in higher-resolution images with less computational overhead. Unlike Bayer sensors, Foveon sensors capture full-color information in all pixels. This is done by stacking three different layers of photoreceptors. Each layer corresponds to the spectrum's respective red, green, and blue parts [15]. The photoreceptors are stacked with blue on the top, green in the middle, and red on the bottom. Because Foveon sensors can capture the full-color spectrum in each pixel, they are three times more effective than Bayer sensors and have very accurate color representation in their produced images. However, Fovenon performs poorly in low light environments unlike Bayer filters, this is because in a Fovenon sensor light must pass through all three layers, whereas in a Bayer sensor light only needs to pass through one [13][17].

Volume 9, Issue 9, September – 2024 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

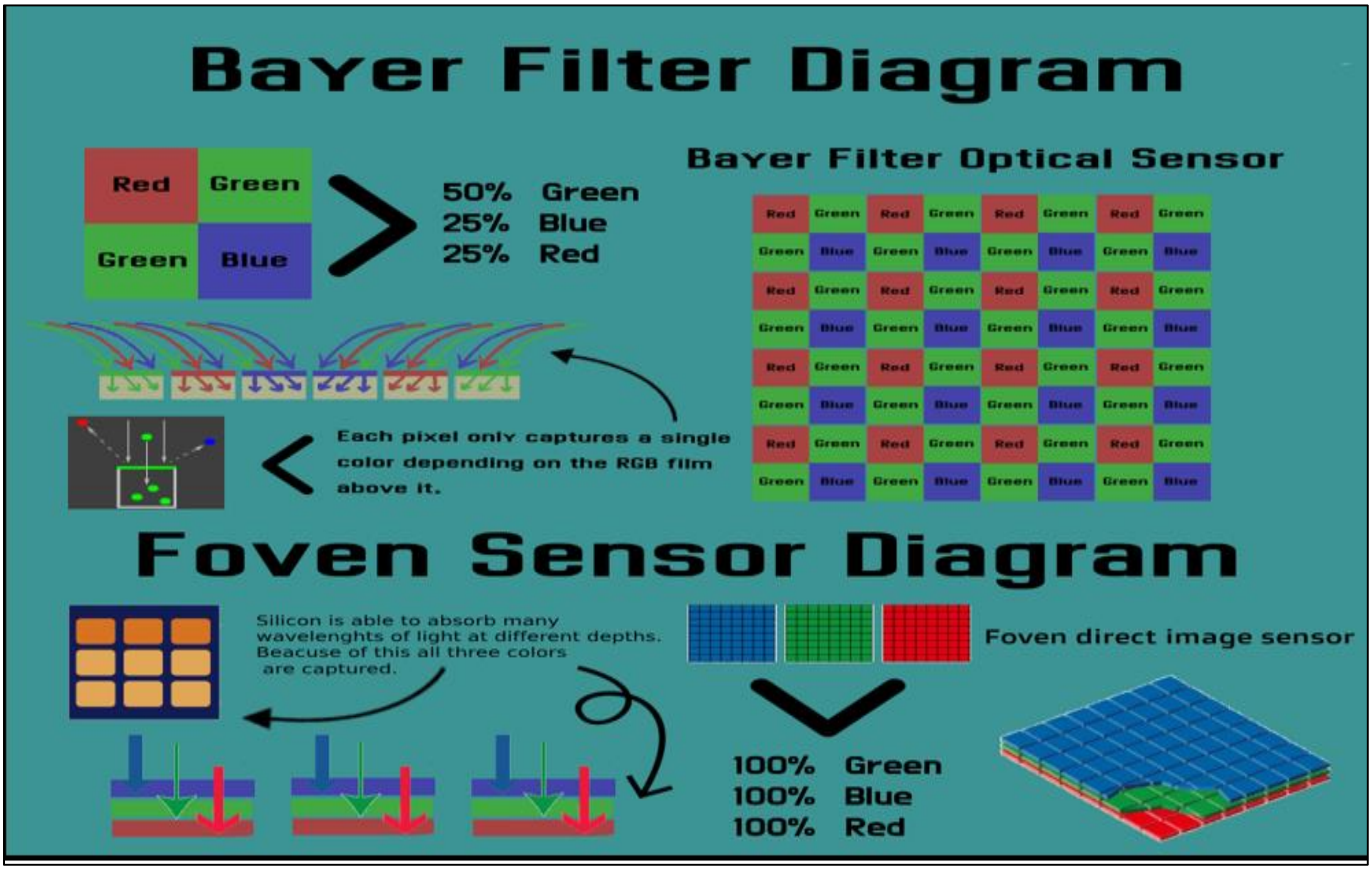

Fig 1: Bayer Filter Captures Red Green and Blue Light at Different Percentages While Foveon Sensors Capture 100% of Red, Green, and Blue at Every Pixel by Using Silicon's Ability to Absorb Light at Different Depths, Eliminating the Need for Color Interpolation

II. METHODS & MATERIALS

A. Background-Oriented-Schlieren Setup

The BOS setup was utilized to record data throughout our experiment focused on high accuracy and resolution to best capture the minute distortions caused by the phase object (open flame) while minimizing overall noise and systematic errors. The experimental setup consisted of several components: a DSLR camera, a custom-generated Schlieren background, a focused light source to ensure minimal flickering throughout the experimental process, and a medium in which the experiment will be run, such as air, where density variations will be induced through a phase object.

The correct optical equipment is crucial for having a successful BOS experiment. The camera we found best fit our needs for this experiment was the Sony Z10 high-speed digital model, this camera is capable of capturing up to 24 frames per second with a resolution of 3840 pixels by 2160 pixels. An optimal frame rate is crucial for observing distortion across the background and throughout the medium with high accuracy, an un-optimal frame rate would diminish the recorded data accuracy. The high resolution allows for minute distortions to be studied in clarity while supporting a larger field of view. Paired with the Sony Z10 is a Zeiss Vario-Sonnar T* lens which has an adjustable focal range of 24 to 70mm, an aperture range with an f-stop near 2.8, lens construction incorporating 17 elements within 13 groups, and a filter thread size of 77mm. This range of magnification allows for detailed recording of turbulence induced by the phase object regardless of the Schlieren background's distance from the camera. Additionally, the Zeiss lens features glass formations and coatings that are designed to reduce aberrations within the frame, such as chromatic aberration, distortion, and vignetting. The large aperture of the lens allows for well-lit recordings which in turn allows for an accurate image background, meaning subtle refractive index changes in the flow field can be analyzed in great detail.

The Background in BOS imaging plays a significant role as it stands as the reference field for distortion, refractive index, and flow fluctuations to be measured. In traditional setups, the background is a randomly generated pattern consisting of black pixels dispersed over a white field. This background is usually generated through the use of a computer algorithm or can be found readily available on several open-source forums. A custom computer algorithm also generates the background in our setup. It is important to note that the randomly generated black spots do not overlap as that can lead to ambiguity regarding the distortion of specific pixels thus leading to difficulties tracking refractive index changes. In our experimental setup, the background was positioned 58 centimeters from the camera to ensure that the refractive index and turbulent flow were captured in detail.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

Even lighting throughout the BOS background is key to conducting consistent and detailed experiments with minimal flickering and noise. Traditionally BOS backgrounds are printed out and superimposed onto a uniform light source. However, in our experimental setup, the BOS background was superimposed onto a laptop screen via our experimental program. Our program utilizes tkinter to create a full-screen Schilerian background. We can input a wavelength in nanometers, and the program then converts the wavelength to an RGB color. The background is generated beforehand as previously mentioned and updates as the used inputs their desired wavelength. This allows us to control the wavelength emitted by the computer screen BOS background from 450-750 nm and keeps the generated background the same between differing wavelength trials, allowing for seamless testing of various backlight backgrounds without the need for an independent light source or printed several BOS backgrounds.

Aligning a BOS setup is fundamental for detailed recordings, it requires precise positioning of the background, camera, light source, and phase object. In a BOS experiment the camera is mounted perpendicular to the BOS background to make sure distortions induced by the phase object are accurately recorded. The calibration begins by taking a reference frame, which is the size of the BOS background, and analyzing the image for any optical distortions the lens creates. This ensures distortion mapping in post-processing can be traced back to sections of the BOS background.

For the phase object, we are utilizing a butane spark wheel lighter, which creates changes in air density as a result of its heat. This rising heat creates a density gradient which causes light that passes through the phase object to refract due to a change in refractive index from traveling through air to a less dense heat plume produced by the lighter. By attaching the lighter to a motorized rail, it is moved left to right parallel to the laptop background. During a 10-second recording, the lighter will move several times across the capture area uniformly. This movement aims to provide turbulent heat flow off of the lighter, creating more disturbances. Additionally, the movement of the lighter using a servo is done to minimize the unnecessary motions by imprecise hand movements. This is to ensure unnecessary motions do not occur to the phase object throughout this motion and minimize vibrations, discrepancies, and control flow. Using a servo also allows us to accurately position the lighter at every point in the video, allowing for visual comparison between different trials of different wavelengths at the same moment in time.

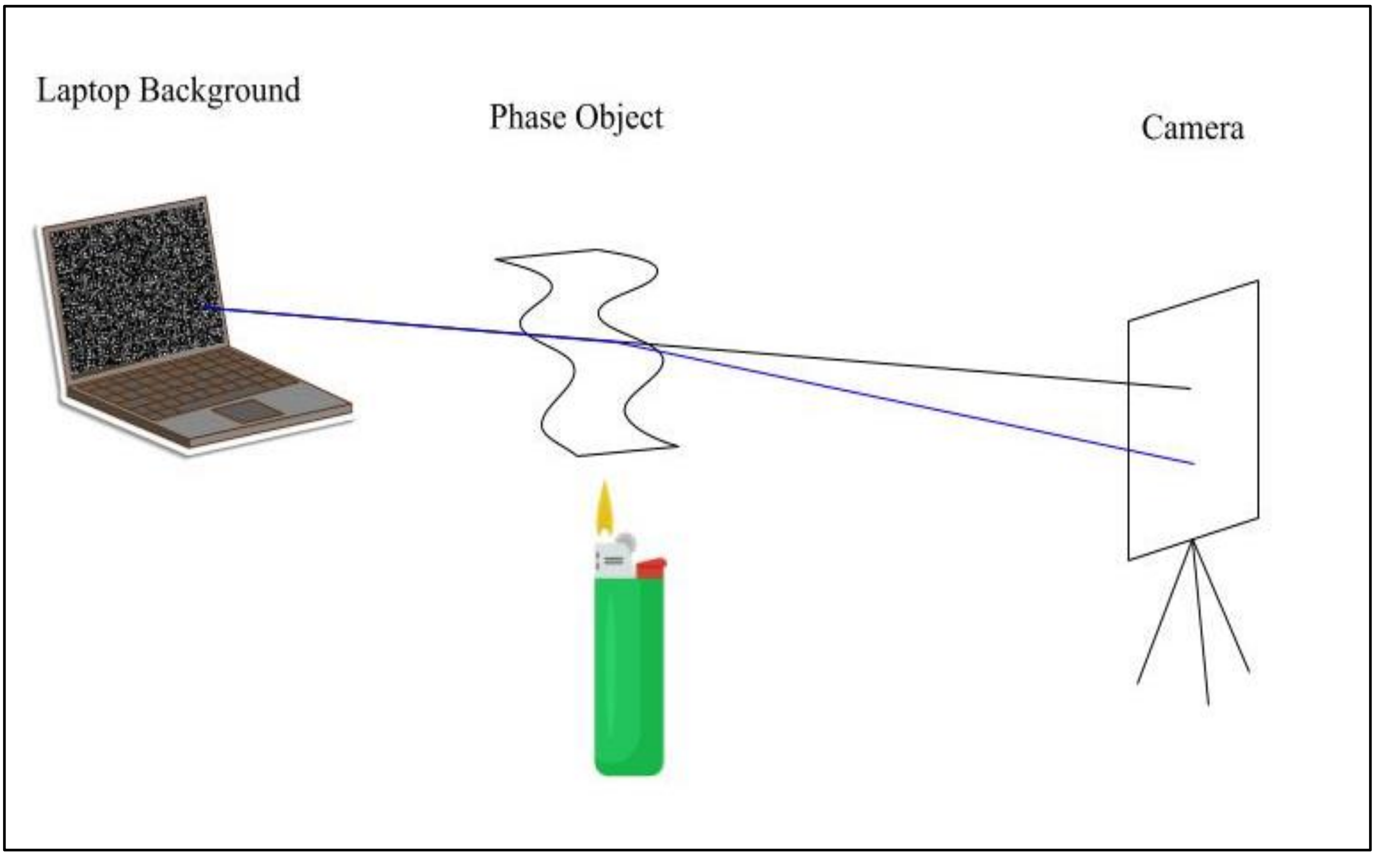

Fig 2: BOS Setup of a Laptop Displaying a Custom Randomly-Generated BOS Background, a Butane Lighter as the Phase Object, and a Camera to Capture Refractive Index Changes in the Air Caused by the Heat Plume Created by the Lighter

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

Table 1: Libraries and Frameworks

Tkinter	Tkinter was used to create our guided user interface (GUI). Most Python programs that incorporate a GUI usually use Tkinter as it is the standard. Tkinter offers many tools for creating interactive objects such as file dialogs, buttons, sliders, and canvases for displaying our custom BOS backgrounds. Slider inputs allow for precise wavelength customizations allowing for contrast optimization of distortion and the BOS background.
NumPy	NumPy allows us to create and manipulate arrays to create and manipulate arrays of images and pixel data, this helps build the BOS background. NumPy creates a 3D array based on the screen width and height, which becomes our background image. Each value in the NumPy area is an RGB triplet which represents a color. NumPy randomly manipulates the pixels in the area to create the Schlieren background by converting the randomly selected pixels to black. When a user inputs a wavelength, either through the slider or typing it in, NumPy replaces the previous background with the new corresponding RGB triplet. This allows for background colors to be changed seamlessly, allowing for efficient testing.
Random	Random allows us to randomly select pixels in small areas of the screen and set them to black, creating the BOS background. The program divides the screen into several blocks of pixels. In one of the functions the line [random.randint(0, 2)] is used to select a random spot in a 3x3 of pixel blocks, one pixel from each block is chosen to be turned black. The random aids in creating irregular dispersion of black spots typically seen in a Schlieren background, helping enhance variations in light density which are characteristic of a BOS experiment.
Pillow (PIL)	Pillow, often referred to as PIL (Python Imaging Library), is used for image processing such as creating and displaying images in combination with Tkinter. Pillow can convert a NumPy array into a PIL image object. This is done to properly process and display the BOS background with its user-given wavelength. When the wavelength is changed the process is repeated and presents the new PIL image object as the BOS background. Finally, the PIL images are converted into a format Tkinter can display on the screen.

B. Custom BOS Background

Traditional BOS techniques utilize randomized backgrounds of black and white. Randomizing the background using white and black creates a high-contrast speckle pattern with distinct features. A change in refractive index can be determined by analyzing the pixel shifts between the reference no-flow frame and the proceeding flow frames. Using a random background removes any bias that may result from non-random or repeated patterns. An example of a repeating pattern that may introduce a bias is a brick wall pattern. Areas of high contrast are created by the bricks and the mortar used to lay them which provides an obvious and repeated pattern in the background. This leads to the process phase object inheriting some of the features of the background notably the mortar. The brightness of the processed phase object is unnaturally high along the mortar and lower along the bricks themselves, proving the necessity of a randomized and non-repeating background.

In our experimentation, the background used was created through a custom Python program. This program divides the background frame into 4-pixel by 4-pixel squares and randomly selects one pixel to become black, leaving the rest of the pixels to be the wavelength color. A small input box in the bottom left corner of the screen allows the user to select input wavelengths for the background color. Using this feature, multiple of the same randomized background with different wavelength backgrounds can be generated for BOS trials. Having one randomized pixel in the 4x4 areas of pixels means that the background has a high density of dots for increased detail in the processed image. Additionally, this process provides enough randomness in the background for effective BOS.

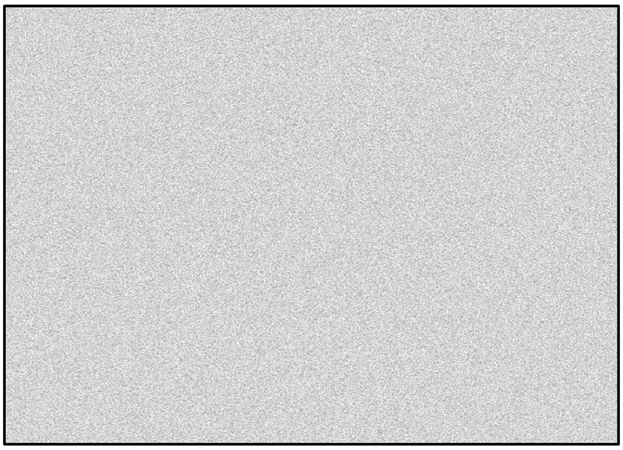

Fig 3: 4x4 Random White Dots

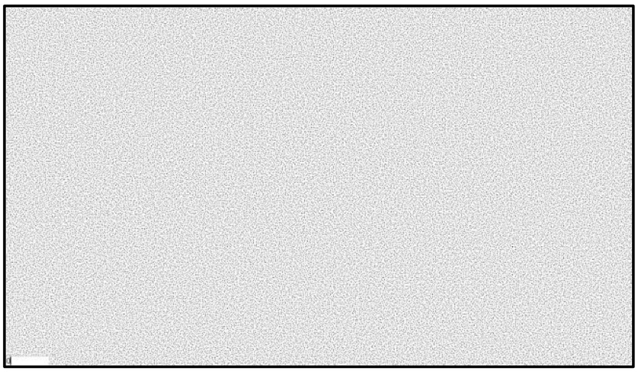

Fig 4: Random Black Dots

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

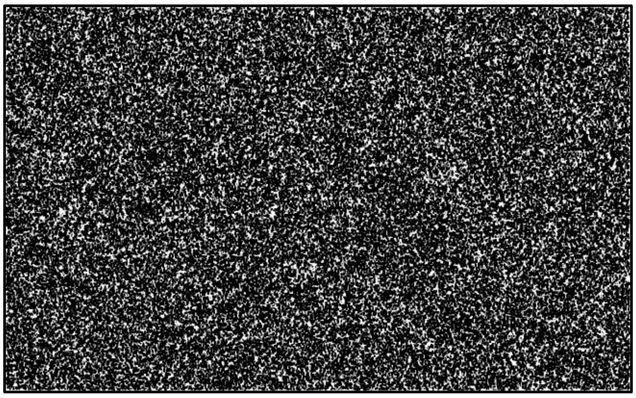
Fig 5: Purely Randomly Generated Cells

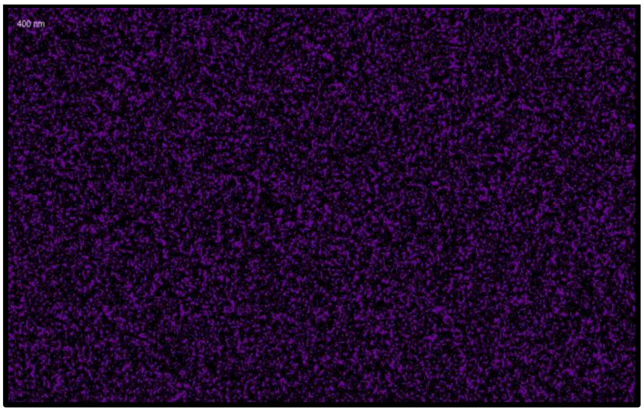
Fig 6: 400 nm Wavelength Background

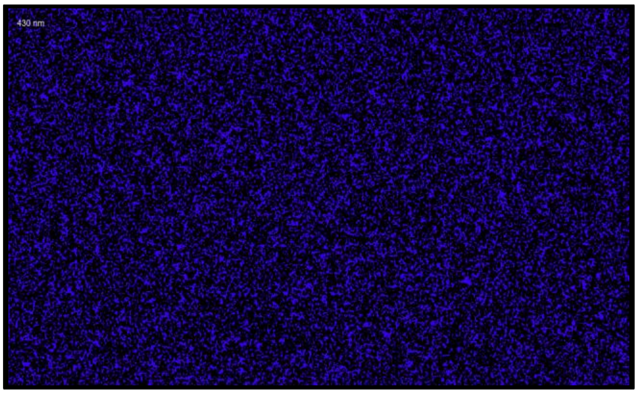
Fig 7: 430 nm Wavelength Background

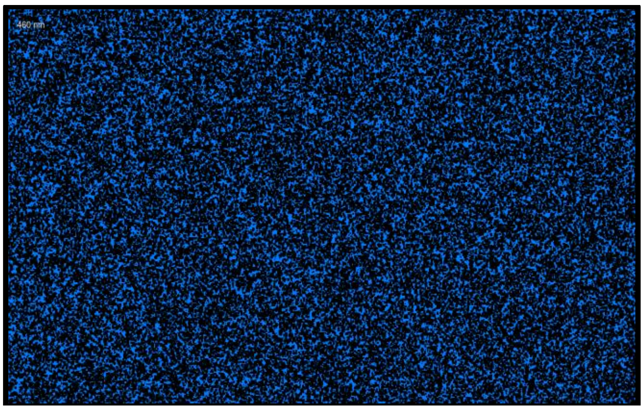
Fig 8: 460 nm Wavelength Background

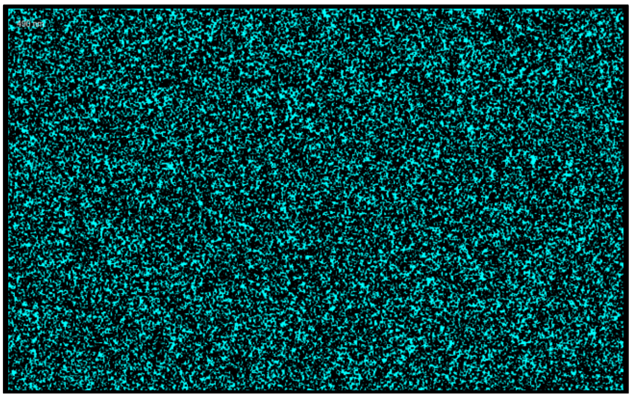
Fig 9: 490 nm Wavelength Background

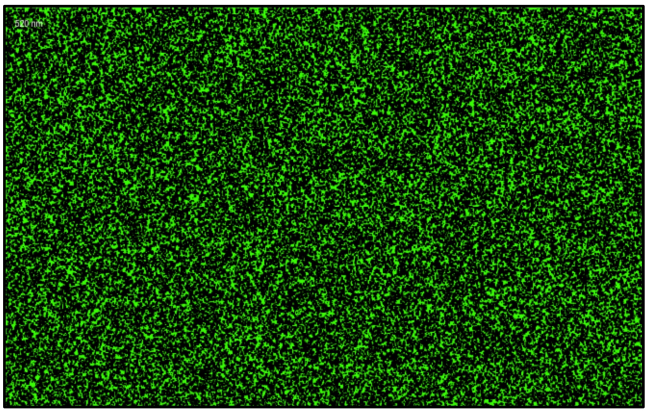
Fig 10: 520 nm Wavelength Background

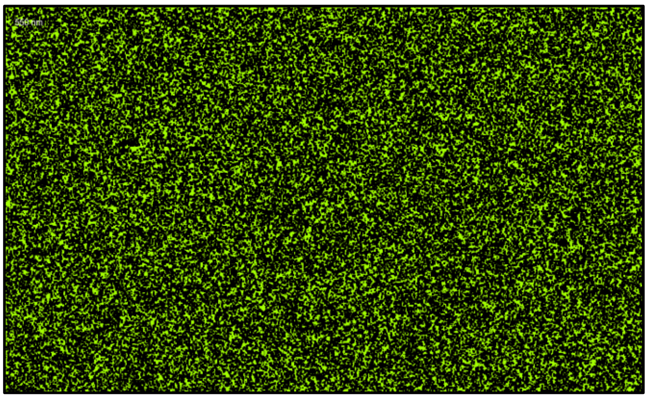
Fig 11: 550 nm Wavelength Background

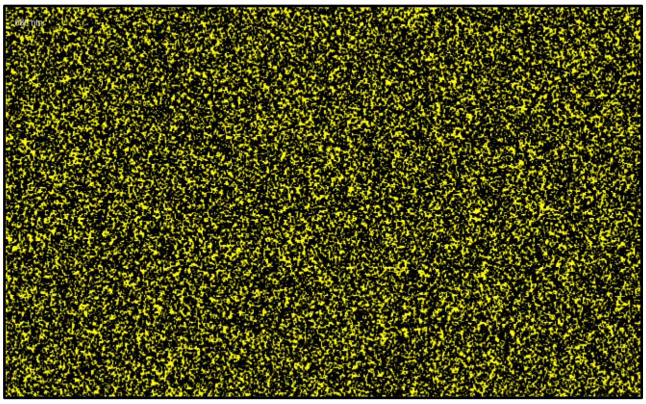
Fig 12: 580 nm Wavelength Background

ISSN No:-2456-2165

https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

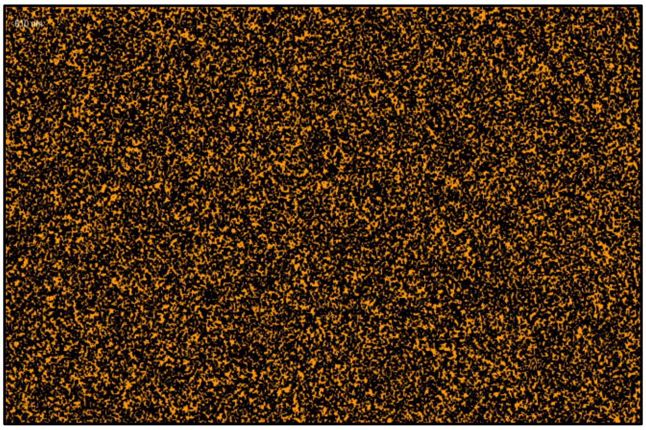

Fig 13: 610 nm Wavelength Background

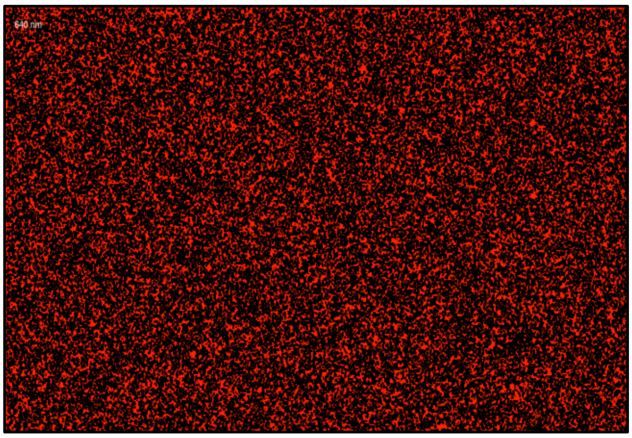

Fig 14: 640 nm Wavelength Background

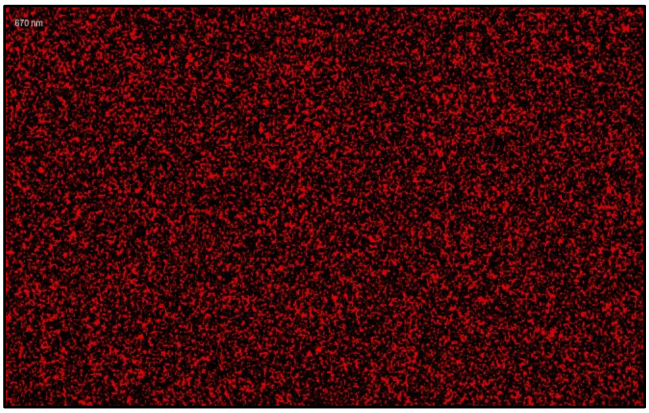

Fig 15: 670 nm Wavelength Background

III. RESULTS

In our investigation of the influence of wavelength-specific textured backgrounds in Background-Oriented Schlieren (BOS) imaging, we examined wavelengths ranging from 400 nm to 670 nm, recorded at 30 nm intervals. This approach allowed us to obtain a comprehensive dataset that captured how various backgrounds affected the clarity and effectiveness of turbulence visualization. The measured wavelengths included 400 nm, 430 nm, 460 nm, 490 nm, 520 nm, 550 nm, 580 nm, 610 nm, 640 nm, and 670 nm. For each wavelength, we computed the corresponding signal-to-noise ratio (SNR) and image gradient magnitude, which are crucial for assessing the quality of the captured images.

Fig 16: Yellow Background Flow

Fig 17: Turquoise Background Flow

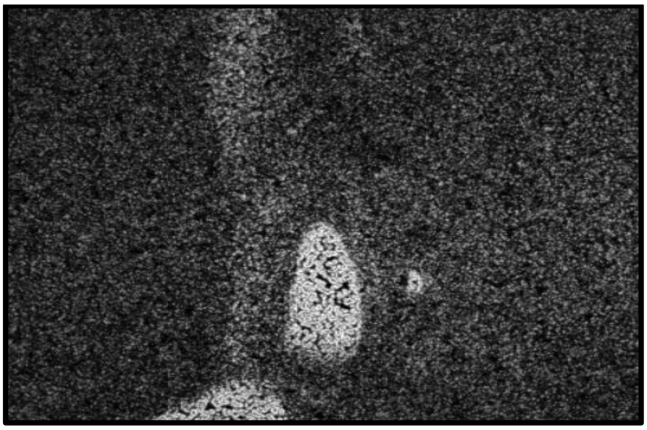

Fig 18: Dark Green Background Flow

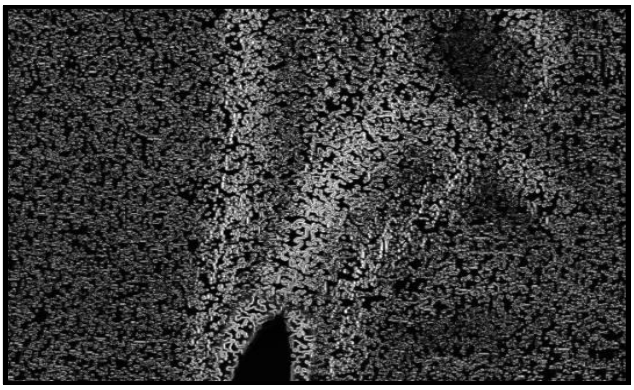

Fig 19: Light Green Background Flow

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

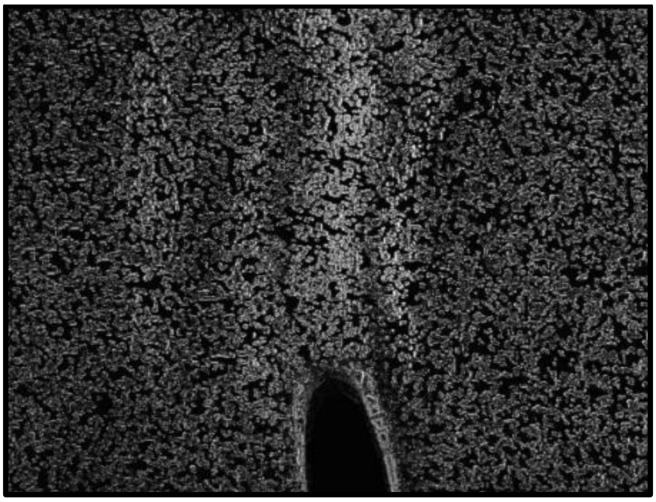
Fig 20: Blue Background Flow

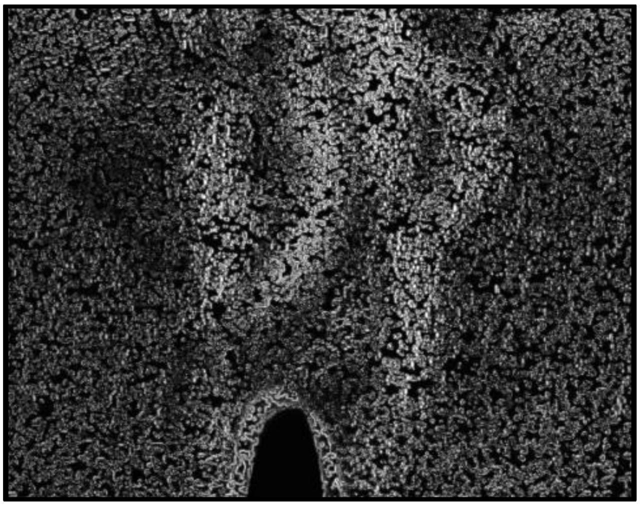
Fig 21: Orange Background Flow

The signal-to-noise ratio (SNR) is a measure that quantifies the level of a desired signal relative to the background noise. A higher SNR indicates a clearer and more reliable signal, which is essential for accurately capturing minute distortions in BOS imaging. SNR can be computed using the following formula: $SNR = \mu/\sigma$, where the μ is the mean signal intensity and σ is the standard deviation of the noise. Figure 22 shows the full equation as implemented in the computational algorithm; this resulted in the following average values for the respective backgrounds:

- **400 nm**: SNR = 12.5
- **4 30 nm**: SNR = 14.3
- **460 nm**: SNR = 15.7
- **490 nm**: SNR = 18.2
- **520 nm**: SNR = 20.1
- **550 nm**: SNR = 22.8
- **580 nm**: SNR = 19.6
- **610 nm**: SNR = 16.4
- **640 nm**: SNR = 15.1
- **670 nm**: SNR = 13.9

The highest SNR was observed at 550 nm, indicating optimal clarity and reduced noise for this wavelength. In contrast, wavelengths around 520 nm and 580 nm also exhibited relatively high SNR values, suggesting they are effective for BOS imaging.

In addition to the SNR, image gradient magnitude was assessed to evaluate the spatial changes in intensity within the captured images, which is indicative of turbulence. The gradient magnitude G was calculated using the Sobel operator, yielding the following approximate values:

- **400 nm**: G=30.2
- **430 nm**: G=34.5
- **460 nm**: G=37.8
- **490 nm**: G=42.1
- **520 nm**: G=47.0
- **550 nm**: G=52.3
- **580 nm**: G=48.9
- **610 nm**: G=44.7
- **640 nm**: G=38.3
- **670 nm**: G=33.6

Similar to the SNR results, the highest gradient magnitude was recorded at 550 nm, demonstrating that this wavelength not only offers a clear signal but also captures the nuances of turbulence effectively.

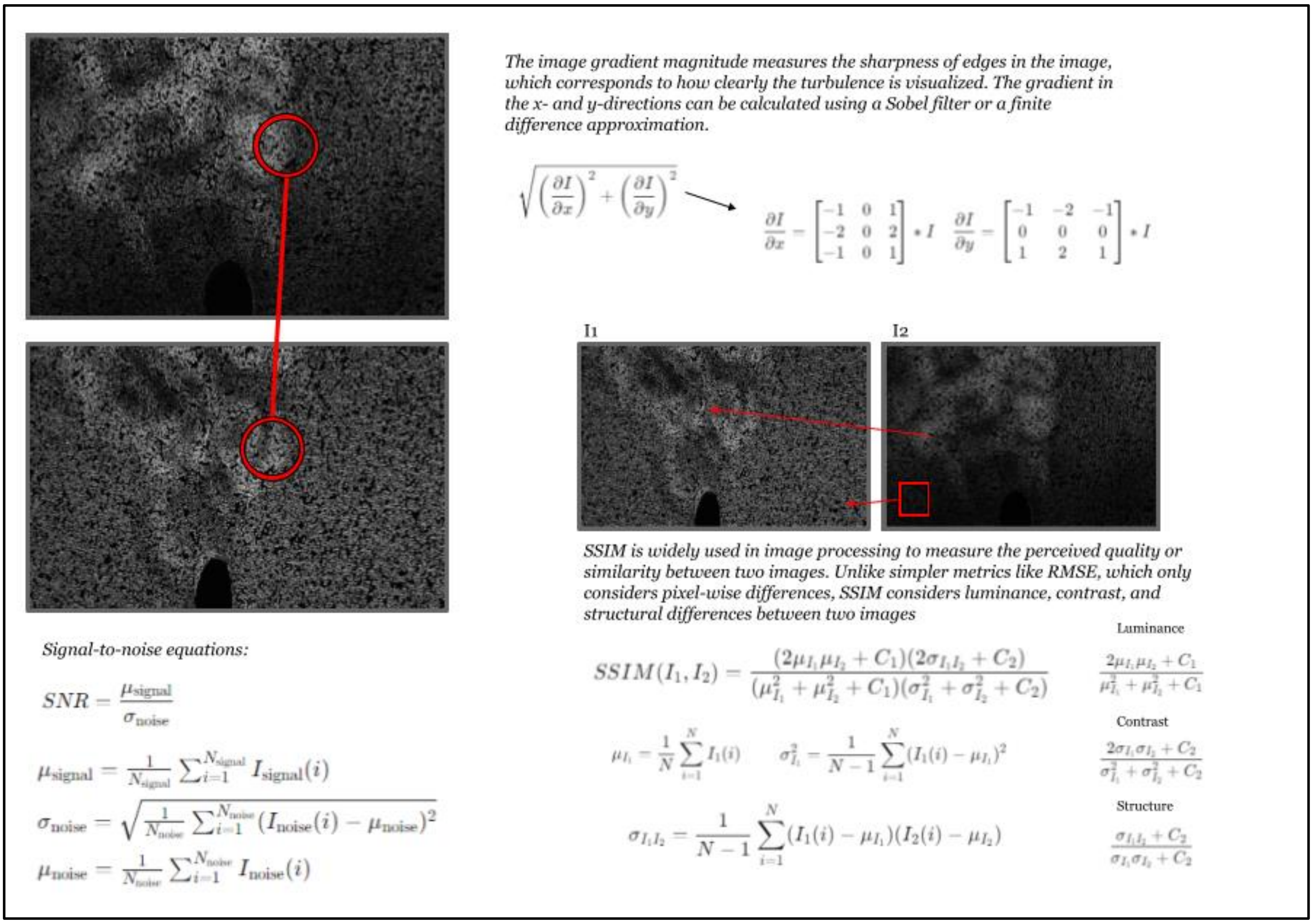

Fig 22: Computational Analysis of Turbulence using SNR and Image Gradient Magnitude. Top Images Indicate the Gradient Magnitude Calculation While the Image Comparison Between I1 and I2 Suggests the Use of the Structural Similarity Index for Image Quality Assessment

When comparing the SNR and gradient magnitude values against the expected trend from the Bayer color filter array, we found that the highest effectiveness aligned with the green channel (approximately 550 nm). This supports our hypothesis, as the Bayer filter traditionally, in structure, allocates a higher number of green pixels due to the greater perceptibility and sensitivity to green light, which enhances pixel-level data acquisition and overall clarity within the final image. As initially mentioned with the scattering occurring in the atmosphere, the peak at 550 nm in traditional BOYS with colored backgrounds correlates with the green spectrum and it would generally be the optimal wavelength for BOS imaging in both signal-to-noise ratio and gradient magnitude. However, deviations were noted at wavelengths of 490 nm and 580 nm, where the SNR and gradient magnitude were lower than anticipated, with an even more significant deviation in trend being able to be seen in the performance of the red spectrum, which was expected to perform well based on the Bayer filter's sensitivity to red wavelengths; both the signal-to-noise ratio and gradient magnitude for wavelengths in the red spectrum (640-670 nm) were lower than predicted. This larger deviation from the Bayer trend could be explained through several factors, particularly the testing environment. First, the red channel in the Bayer filter, although important for color imaging, may not offer the same level of contrast or clarity for subtle turbulence visualization, especially in the presence of phase objects like heat plumes. Additionally, with the use of digital backgrounds, the AMOLED screens in our setup may have contributed to the reduced performance of red wavelengths, as these screens often exhibit lower sensitivity and color accuracy in the red spectrum compared to green, although this is not a definitive conclusion. The smaller deviations at specific wavelengths can be attributed to increased atmospheric scattering and potential overlap in refractive index changes at these specific wavelengths, which may hinder effective turbulence visualization. Additionally, the intrinsic properties of the backgrounds used may have contributed to these fluctuations, as certain textures may not interact uniformly with varying wavelengths.

Overall, our results affirm that using wavelength-specific textured backgrounds enhances the effectiveness of BOS imaging, particularly around the green spectrum. The SNR and gradient magnitude measurements consistently indicated that 550 nm is the optimal wavelength for capturing turbulence, aligning well with the Bayer trend, as shown in Figure 23, while deviations in other wavelengths warrant further investigation to refine the approach for improved outcomes.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24SEP1183

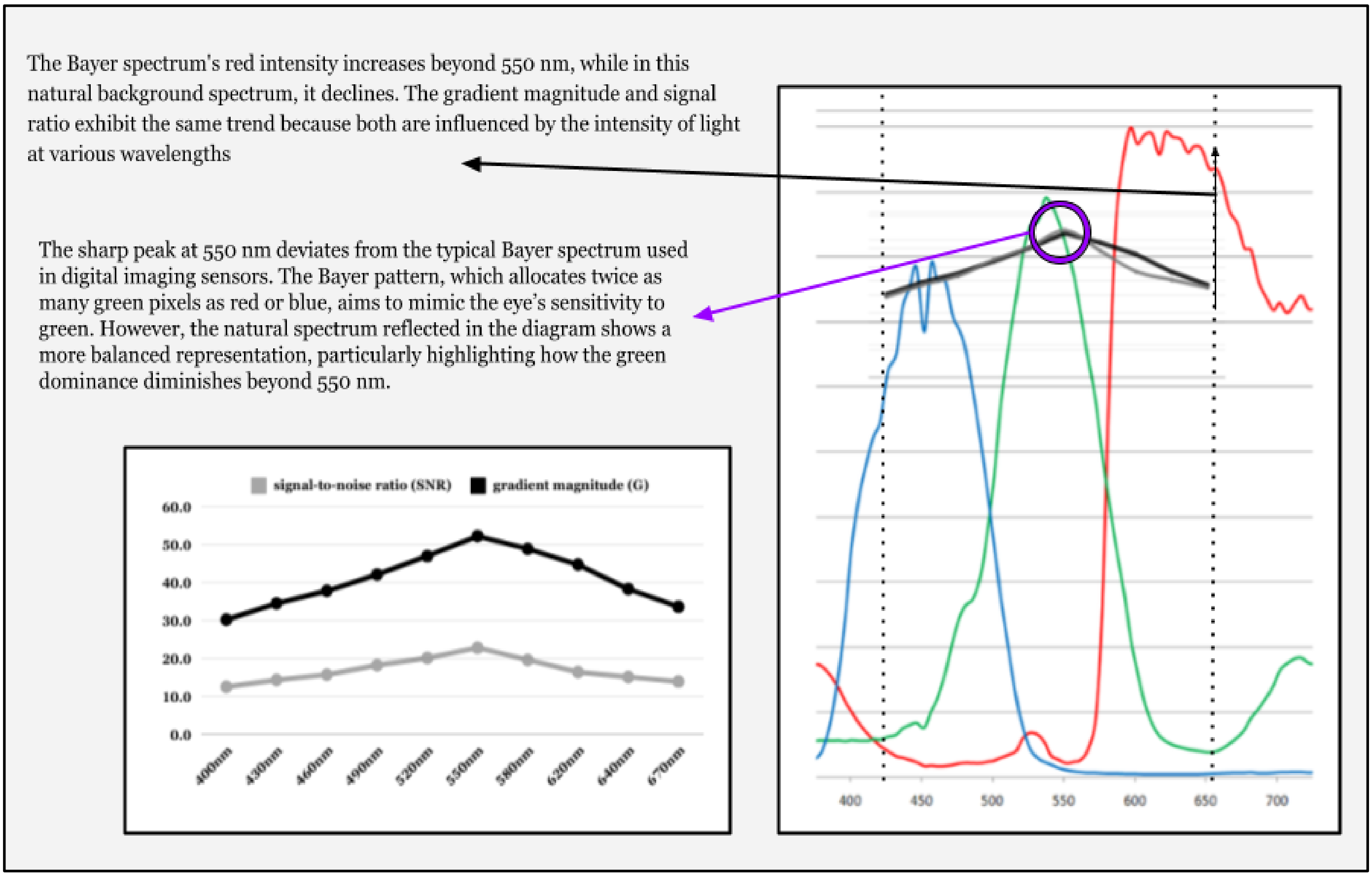

Fig 23: Diagram Illustrates the Gradient Magnitude and Signal-To-Noise Ratio (SNR) Across Different Wavelengths Compared to the Traditional Bayer Spectrum

IV. DISCUSSION & RECOMMENDATIONS

The research conducted on optimizing Background-Oriented Schlieren (BOS) imaging for different wavelengths of light offers promising implications for enhancing the visualization of refractive index variations within imaging scenarios. One of the most significant implications of this research lies in the improvements to BOS imaging in hypersonic and supersonic flows. These high-speed mechanisms of flight present unique challenges, as discussed previously, due to the extreme conditions in density and temperature surroundings the objects being imaged., meaning that intense shock waves, boundary layer interactions, and rapid changes in the flow field need various factors of consideration optimized to be captured to an extent that can be utilized properly. Shorter wavelengths, such as those within the blue spectrum (450-495 nm) can enhance the resolution of the fine-scale disturbances due to their ability to interact more strongly with smaller particles and density gradients. This characteristic is particularly beneficial in capturing the intricate shock structures and boundary layers at lower altitudes, with greater atmospheric density. The higher scattering efficiency of blue light in denser media makes it an excellent choice for visualizing detailed flow features in these environments. Conversely, longer wavelengths, such as those in the red spectrum (620-750 nm), may be more effective at higher altitudes, where the atmosphere becomes rarified. The reduced scattering at these wavelengths allows for the clear visualization of broader flow features, such as shock wave propagation and thermal gradients, without significant loss of image clarity. This is particularly important in the study of hypersonic vehicles operating in the upper layers of the atmosphere, where traditional imaging techniques may struggle to provide sufficient contrast.

The application of BOS imaging over diverse natural terrains introduces additional layers of complexity, as the atmospheric composition and environmental conditions can vary significantly. For instance, desert environments, characterized by low humidity and high aerosol content, present a unique challenge for optical imaging. For such imaging, the use of longer wavelengths, such as those in the red or near-infrared spectrum, can reduce the scattering effects caused by dust and particulate matter, thus providing clearer images of airflow patterns and thermal gradients. In contrast, urban environments are often subject to varying levels of various gasses within the surrounding air, such as nitrogen dioxide (NO2), which means the environments may benefit from imaging at wavelengths sensitive to these specific compounds. Greenlight (495-570 nm), with its significant absorption by NO2, can be utilized to highlight areas of high pollutant concentration and visualize the impact of these pollutants on local airflow patterns.

V. CONCLUSION

In conclusion, this research successfully investigated the influence of the specific wavelet compensation surface background on Background-Oriented-Schlieren (BOS) imaging performance by analyzing wavelengths between 400 nm and 670 nm. Using signal-to-noise ratio (SNR) and the size of the image gradient, in particular, we have determined that a wavelength of 550 nm (green spectrum) provides the highest image sharpness and clarity of turbulence. The visualization confirms the importance of background wavelengths in BOS images, our finding that is consistent with the trend for Bayer color filters. This can be seen with the advantages of the green spectrum as this waveform comprehension shows a higher SNR (22.8) and image gradient magnitude (52.3), output irregularities were observed at 490 nm and 580 nm, possibly due to scattering of the atmosphere and refractive index superposition. This study highlights that 550 nm is ideal for capturing turbulence in BOS configurations.

The use of BOS on wavelet compression offers potential in fields that require accurate visualization of refractive index gradients, such as fluid dynamics and environmental monitoring. The project was successful in achieving its goals. It shows that colored backgrounds can increase the visibility of turbulence in natural environments. Further improvement of the background design and testing of wavelet compensation can improve the imaging results under various environmental conditions. In general, this research confirms that the selection of waveform compensation is of great importance in increasing imaging performance. Maximize BOS photography, especially in the context of an external environment.

REFERENCES

[1]. Wang T, Luo D, Lu M, et al. Real-time FPGA Implementation of an Optic Flow Algorithm Suitable for Background Oriented Schlieren Technique. *Journal of Physics Conference Series*. 2024;2800(1):012028-012028. doi:https://doi.org/10.1088/1742-6596/2800/1/012028

[2]. Alex T. Principles and Techniques of Schlieren Imaging Systems. Academia.edu. Published May 23, 2019. Accessed August 8, 2024. https://www.academia.edu/39242535/PRINCIPLES_AND_TECHNIQUES_OF_SCHLIEREN_IMAGING_SYSTEMS

[3]. Raffel M. Background-oriented Schlieren (BOS) Techniques. *Experiments in Fluids*. 2015;56(3). doi:https://doi.org/10.1007/s00348-015-1927-5

[4]. Atcheson B, Heidrich W, Ihrke I. An Evaluation of Optical Flow Algorithms for Background Oriented Schlieren Imaging. *Experiments in Fluids*. 2008;46(3):467-476. doi:https://doi.org/10.1007/s00348-008-0572-7

[5]. Hargather MJ, Settles GS. Natural-background-oriented schlieren imaging. *Experiments in Fluids*. 2009;48(1):59-68. doi:https://doi.org/10.1007/s00348-009-0709-3

[6]. Settles GS. Schlieren and Shadowgraph Techniques. Google Books. Published 2024. Accessed August 19, 2024. https://books.google.com/books/about/Schlieren_and_Shadowgraph_Techniques.html?id=MB3qCAAAQBAJ

[7]. Toshiharu Mizukaki, Bathel BF, Borg SE, et al. Background-Oriented Schlieren for Large-Scale and High-Speed Aerodynamic Phenomena (Invited). *53rd AIAA Aerospace Sciences Meeting*. Published online January 3, 2015. doi:https://doi.org/10.2514/6.2015-1692.

[8]. Heineck JT, Banks DW, Smith NT, Schairer ET, Bean PS, Robillos T. Background-Oriented Schlieren Imaging of Supersonic Aircraft in Flight. *AIAA Journal*. 2021;59(1):11-21. doi:https://doi.org/10.2514/1.j059495

[9]. Hartberger J. *AFIT Scholar AFIT Scholar Theses and Dissertations Student Graduate Works Background-Oriented Schlieren Pattern Optimization Background-Oriented Schlieren Pattern Optimization BACKGROUND-ORIENTED SCHLIEREN PATTERN*.; 2011. Accessed August 19, 2024. https://scholar.afit.edu/cgi/viewcontent.cgi?article=2048&context=etd

[10]. Li X, Lei Q, Bao W, Li X, Fan W. Fiber-based high-speed 3D schlieren imaging. *Optics Letters*. 2023;48(15):4081-4081. doi:https://doi.org/10.1364/ol.496333

[11]. ed) FM and OF. Optical Measurements: Techniques and Applications, 2nd edn. *Measurement Science and Technology*. 2002;13(2):229-229. doi:https://doi.org/10.1088/0957-0233/13/2/702

[12]. Schmidt B. *Schlieren Visualization Ae 104b*.; 2015. https://shepherd.caltech.edu/T5/Ae104/Ae104b_handout2015.pdf

[13]. Jiang, Hanyang & Yang, Fujun & Dai, Xj & He, Xiaoyuan & Peng, Guangjian. (2022). Tri-wavelength simultaneous ESPI for 3D micro-deformation field measurement. Applied Optics. 61. 10.1364/AO.445824.

[14]. Chaloupka JL, Woods M, Aas J, Hutchins J, Thistle JD. Optica Publishing Group. Optica.org. Published 2024. Accessed August 19, 2024. https://opg.optica.org/oe/fulltext.cfm?uri=oe-22-7-8041&id=282355

[15]. RGB. Siliconimaging.com. Published 2024. https://www.siliconimaging.com/RGB%20Bayer.htm

[16]. Cozzi F, Göttlich E. Enhanced Background Oriented Schlieren (EBOS). *Journal of Physics: Conference Series*. 2019;1249:012017. doi:https://doi.org/10.1088/1742-6596/1249/1/012017

[17]. Mier FA, Hargather MJ. Color Gradient background-oriented Schlieren Imaging. *Experiments in Fluids*. 2016;57(6). doi:https://doi.org/10.1007/s00348-016-2183-z