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Ground-Level Measurements of the Modulation Transfer Function of a Brownout Cloud

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The paper addresses the problem of measuring the Modulation Transfer Function (MTF) at or near the ground level of a sandy soil area. Because the MTF provides quantitative information on loss of visual contrast and texture, it can be useful to quantify the loss of visual cues in brownout conditions. The results presented in this paper indicate that it is possible to measure the MTF of a brownout cloud at or near ground level, by analyzing the black/white transitions of an edge on an optical target. Black/sand transitions are also suitable, but less precise. It is possible to interpret a large number of MTF calculations over a range of space and time in ways that succinctly quantify the degradation of visual cues caused by a the brownout cloud. At a given instant in time it is possible to compose contour plots that describe the loss of visibility over wide regions (e.g., an entire landing area). Similarly, the temporal variation in visibility degradation due to the brownout cloud can be plotted to gain a more complete understanding of the brownout problem. The intuitively known fact that small details and ground texture are obscured before larger objects, i.e., that the sediment cloud acts as an optical low-pass filter, is correctly captured quantitatively. Because the size of the optical targets needed for MTF calculations is small, multiple targets could be safely placed in the landing area, which would allow MTF measurements along paths from the pilot's eyes to points in the landing area. These measurements would improve the fundamental understanding of the effects of brownout on handling qualities.

Nomenclature

$\mathbf{F}[\ ]$	Fourier transform
$H(x,y)$	Irradiance, radiant power per unit area
$s(x,y)$	Point Spread Function
$S(\omega_x,\omega_y)$	Fourier transform of the Point Spread Function
t	Time
ω	Spatial frequency
τ	Optical Transfer Function
DVE	Degraded Visual Environment
ERF	Edge Response Function
ESF	Edge Spread Function
FOV	Field Of View
HQ	Handling Qualities
MTF	Modulation Transfer Function
OTF	Optical Transfer Function
PSF	Point Spread Function
PTF	Phase Transfer Function

Introduction

Brownout conditions are often encountered during approach and landing in a desert environment, and involve the entrainment of dust or sand in the rotor downwash. The particles obscure the pilot's field of view, causing loss of visual reference and potentially leading to spatial disorientation. As such, brownout is a Degraded Visual Environment (DVE), a topic of continued importance in the Handling Qualities (HQ) community [1–3]. To navigate and maintain aircraft control, pilots must simultaneously close multiple control loops, and visual cues play a key role. Research has shown visual texture to be a cue of vital importance in this process [3–6]. For example, pilots utilize both "macro-texture" (large objects or, equivalently, low spatial frequency) and "micro-texture" (fine-grained detail, or high spatial frequency) to provide information on the location, attitude, and motion of the aircraft. Brownout can either degrade or fully eliminate these cues, and may lead to loss of control by the pilot, potentially resulting in violent impact of the aircraft with the ground or other obstacles.

Brownout is a complex phenomenon, involving sediment clouds that consist of space- and time-dependent two-phase flows. The complexity of the brownout phenomenon makes the sediment clouds difficult to characterize through quantitative metrics. While a cloud that completely cancels visual cues is intuitively "bad", and one that allows perfect visibility is intuitively "good", quantification of such assessments has been historically problematic. In recent research, the Modulation Transfer Function (MTF) has been proposed as the basis for a quantitative assessment of the visual degradation of a brownout cloud [7, 8].

A number of atmospheric effects can degrade optics, including background irradiance, atmospheric turbulence, and airborne particulates (aerosols) suspended in the atmosphere. Particulates are the key factor for brownout, and can cause contrast reduction and image blur due to the scattering and absorption of light passing through the sediment cloud. The MTF quantifies the loss of contrast as a function of spatial frequency, and is widely used in the optics community to evaluate the performance of optical instruments [9]. As such, it has been demonstrated to have the potential for promoting a more advanced understanding of the brownout phenomenon. For

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example, the MTF could be used to quantify available texture cues for HQ analyses. As a matter of fact, the MTF had been proposed by Hoh as a metric for DVE conditions prior to the development of the ADS-33 handling qualities specification [4], but simpler, if more subjective, pilot opinion-centered criteria were eventually used. Furthermore, the MTF could be used in assessing the fidelity of brownout representations for pilot-in-the-loop flight simulators, to validate that the visual cue degradation is realistic. Taking advantage of the fact that the MTF can be predicted from light scattering theory [9–12], the MTF could also be used in rotorcraft design optimization studies with the goal of brownout mitigation.

A number of factors must be considered when using the MTF for brownout cloud characterization. For example, the MTF of a brownout cloud varies significantly with space and time. Furthermore, visual cues are not equally important in all directions and at all times. As such, analyses using the MTF ought to be properly weighted to reflect actual piloting needs. Likewise, because the MTF is simply a measure of visual cue degradation, some criteria need to be added to assess whether the level of degradation is still acceptable for a given piloting task. With an understanding of these factors, the MTF gives quantitative, spatial frequency-dependent information, can be predicted theoretically from light scattering theory [9–12], and can be measured experimentally [9]. It can thus represent a fundamental building block in constructing a better understanding and quantification of brownout.

A general procedure for calculating the MTF of brownout clouds generated from flight tests, based on the work by Kopeika [9], was proposed in Refs. [7, 8]. There, MTFs were extracted from the frames of the video recording of an optical target (a Siemens star) placed on the side door of a helicopter, filmed from a ground location outside the brownout cloud. While these measurements were useful for methodology development, measurements of much greater potential interest for handling qualities and simulation applications would be along paths from the pilot's location in the cockpit to points in the landing area. Safety-of-flight concerns make such measurements very difficult to obtain, because it is difficult to place and safely secure optical targets of sufficient size in the immediate landing area.

In light of the foregoing, the primary objective of the present work is to present an improved methodology for extracting brownout MTFs at or near ground level, and to propose a technique to safely measure the MTF of a brownout cloud along a path from inside the cockpit to points in the aircraft landing area. Another objective of the paper is to show how information from multiple optical targets can be interpreted over space and time to quantify spatial frequency-dependent visual degradation.

MTF BACKGROUND

In linear optics, the image irradiance (H_i, the radiant power per unit area perceived by the imaging device) can be described by the convolution of the object irradiance (H_o, the irradiance of the object being viewed) with the Point Spread Function (PSF),

$$H_i\left(x',y'\right) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H_o\left(x,y\right) s\left(x'-x,y'-y\right) dx\, dy \qquad (1)$$

where (x',y') describes coordinates in the image plane, (x,y) describes coordinates in the object plane, and $s\left(x',y'\right)$ is the

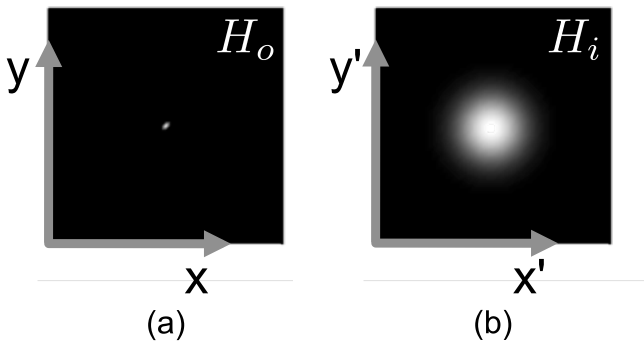

Fig. 1: Basic illustration of the PSF. The object is the point image shown in (a), and the image resulting from a 2-D Gaussian PSF is shown in (b).

PSF, which describes the spreading of irradiance of a point image. An example of the PSF is shown in Fig. 1, in which the object is a single point that is spread by a two-dimensional Gaussian PSF to yield the image. The figure could represent the behavior of a hypothetical optical instrument such as a camera lens or a telescope. From a practical standpoint, the PSF is a result of the combination of effects from all components of the imaging *system*, where *system* is inclusive of everything from the imaging equipment to the environment through which the image is transmitted.

The Optical Transfer Function (OTF) is defined as the Fourier transform of the PSF, scaled to provide a maximum value of unity:

$$\begin{aligned} \text{OTF} &= \tau(\omega) = \tau(\omega_x,\omega_y) \\ &= \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} s\left(x',y'\right)\exp\left\{-j\left(\omega_x x' + \omega_y y'\right)\right\} dx'\, dy'}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} s\left(x',y'\right) dx'\, dy'} \\ &= \frac{S(\omega_x,\omega_y)}{S(0,0)} = \text{MTF}\exp(j\text{PTF}) \end{aligned} \qquad (2)$$

where MTF is the Modulation Transfer Function, PTF is the Phase Transfer Function (which is not as important as the MTF in describing resolution and $S(\omega_x,\omega_y)$ is the Fourier transform of the PSF, in terms of spatial frequency, ω [9]. It should be noted that, although the dividing by $S(0,0)$ normalizes the resulting MTF curve to a maximum value of unity, it is not uncommon for multiple MTF curves to be normalized to a common baseline for the purposes of relative comparison. In the context of brownout, the sediment cloud will affect the spreading of the image irradiance (i.e., the cloud affects $s\left(x',y'\right)$, the PSF), and the MTF is thus a measure of the way in which a brownout cloud transfers spatial modulation from the visual scene to the observer.

Prior works have presented MTF measurements from brownout flight testing as calculated using two methods, namely the square-wave and edge response methods [7–9]. In order to obtain the measurements, a Siemens star was placed on the side of a landing aircraft. In the present work, only the edge response method was utilized for MTF calculations. This method consists of analyzing the black-white transition of a single edge [9, 13] rather than the full optical pattern needed for the square-wave method. The primary strength of this method is its broad applicability, because it eliminates the need for a prefabricated test pattern. In fact, the edge response method can be implemented on any edge in the visual scene that exhibits sufficient contrast. The edge response method can also be used to calculate MTFs for multiple regions of the same image, thus providing the capability to characterize the spatial variation of the brownout cloud at a given instant in time.

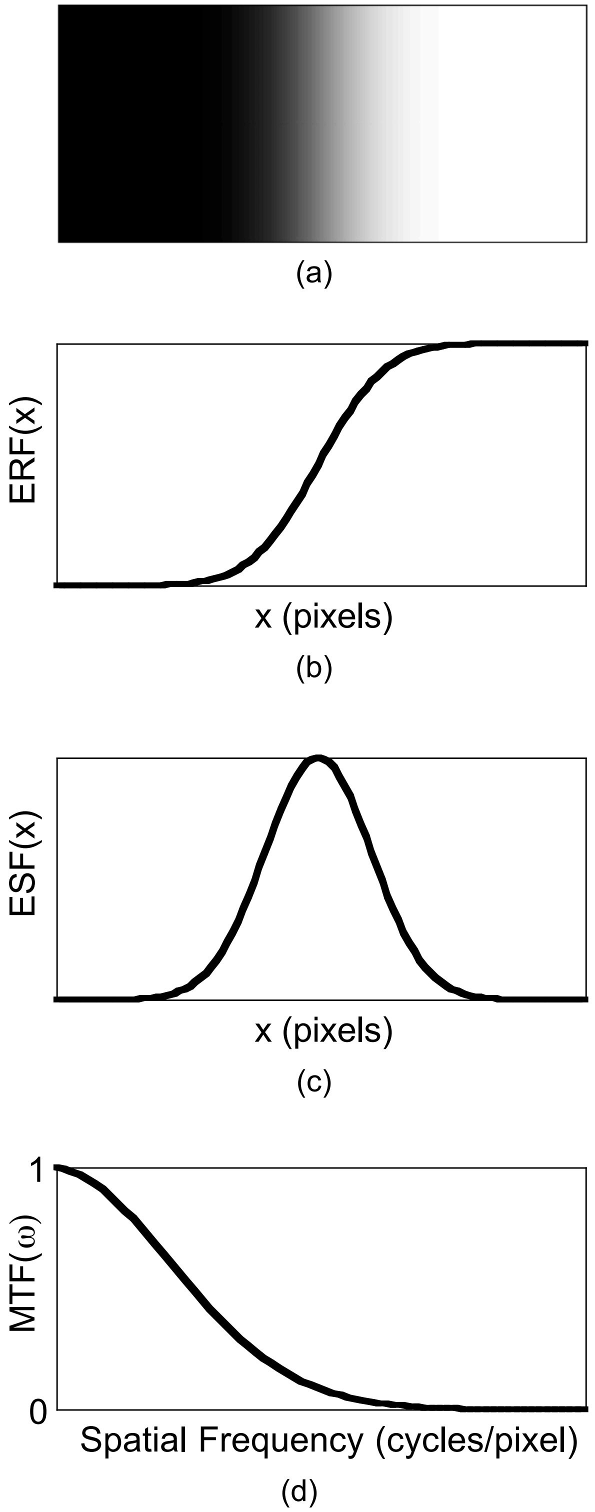

Fig. 2: Edge response method for MTF calculation.

The procedure for calculating MTF using the edge response method [9] is summarized graphically in Fig. 2. For a given edge in the field of view, a mathematical Edge Response Function (ERF) can be defined as the grayscale level variation (or "response") along a line normal to that edge. A "perfectly sharp" edge can be thought of as a step function, however a perfectly sharp edge is not generally possible in practice because there is some distance over which the transition from dark to light is observed. A typical such transition is shown in Fig. 2(a). The ERF is then fit by a suitably-scaled Gaussian Cumulative Distribution Function (CDF), as shown in Fig. 2(b). This fitting process can be automated by defining the limits of the "edge" region as the points at which a rolling average of the grayscale response converges to a consistent value. Variations due to image noise can be minimized by averaging the edge response over five closely-spaced (e.g., separated by one or two pixels) parallel lines that are normal to the edge of interest.

The derivative of the edge response function gives the Edge Spread Function, ESF,

$$\frac{d}{dx}\mathrm{ERF}(x) = \mathrm{ESF}(x) \tag{3}$$

as shown in Fig. 2(c).

It is apparent that the ESF, also referred to as the Line Spread Function (LSF), is the one-dimensional analogue to the two-dimensional PSF given in Eq. 1. Similarly to Eq. 2, then, the Fourier transform of the ESF yields the MTF,

$$\mathbf{F}[\mathrm{ESF}(x)] = \mathrm{MTF}(\omega_x) \tag{4}$$

as shown in Fig. 2(d).

A number of practical considerations in performing MTF calculations using the edge response method have been identified previously [8, 9] and are addressed further in Appendix A.

TEST METHODOLOGY

Optical Targets

The importance of proper edge selection for MTF extraction has been documented in prior work [8]. Figure 3 shows six transition edges, potentially useful for MTF extraction, on a number of optical targets in the test area. They consist of: (a) the edge between adjacent black and white segments of an optical target, (b) the edge between a black segment and the ground, (c) the edge between a white segment and the ground, (d) small black and white "edge strips" affixed to the upper corners of the test patterns, (e) a stripe of black tape placed on a white sandbag at the ground, and (f) a cylinder fitted with black and white coverings.

Location (a) is the most similar to that used in Refs. [7, 8], and can be considered as a baseline. The "black-to-sand" (b)

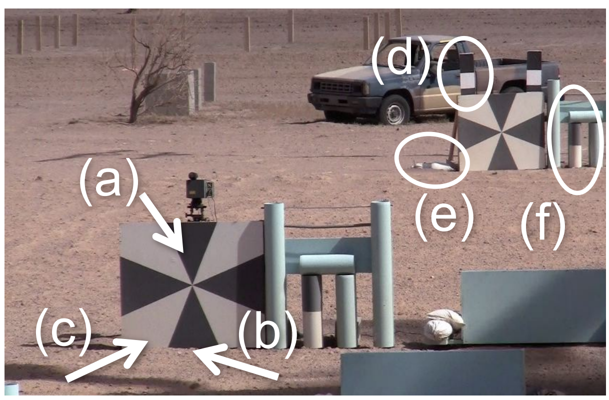

Fig. 3: Locations utilized for MTF extraction.

and “white-to-sand” (c) edges can help determine if the target/ground interface was sufficiently sharp and could provide enough contrast. The small “edge strips” (d) were intended to explore any issues that may arise with the use of small-scale full targets. The black taped sandbag (e) was a somewhat improvised optical target on a heavy object that would not be moved by rotor downwash. The cylinder (f) was included to study the effect of shadows on MTF measurements.

Two key parameters of any MTF curve are its initial magnitude, MTF_0, and spatial frequency cutoff, ω_{cutoff}, both depicted in Fig. 4. Higher values of MTF_0 indicate an optical target that contains greater contrast, and higher values of ω_{cutoff} indicate the presence of a sharper edge. By examining the way in which these values vary for each target over a series of frames from the video recording, an assessment of the repeatability of the MTF measurements for each target can be presented. The validity of this assessment is obviously limited to measurements conducted prior to the onset of the brownout cloud, because then the temporal and spatial variations of the cloud itself would dominate any frame-to-frame variation.

Interpreting MTF Measurements in Space and Time

Because the MTF is defined along an optical path between two points, the MTF of a brownout cloud is at least a five-dimensional quantity: three spatial dimensions (six, if one wants to consider independent positions of the starting and ending point of each optical path), time, magnitude, and spatial frequency. Therefore, interpreting MTF information can be challenging.

Spatial frequency dependency can be simplified by averaging the MTF over two frequency bands, e.g., those that define the macro- and the micro-texture scales. For example:

$$\overline{\mathrm{MTF}}_{\mathrm{macro}} = \frac{1}{2}\int_1^3 \mathrm{MTF}(\omega_x)\, d\omega_x \tag{5}$$

$$\overline{\mathrm{MTF}}_{\mathrm{micro}} = \frac{1}{10}\int_{10}^{20} \mathrm{MTF}(\omega_x)\, d\omega_x \tag{6}$$

where macro-texture is defined by low spatial frequencies, e.g., in the 1–3 cycles/degree range, and micro-texture is

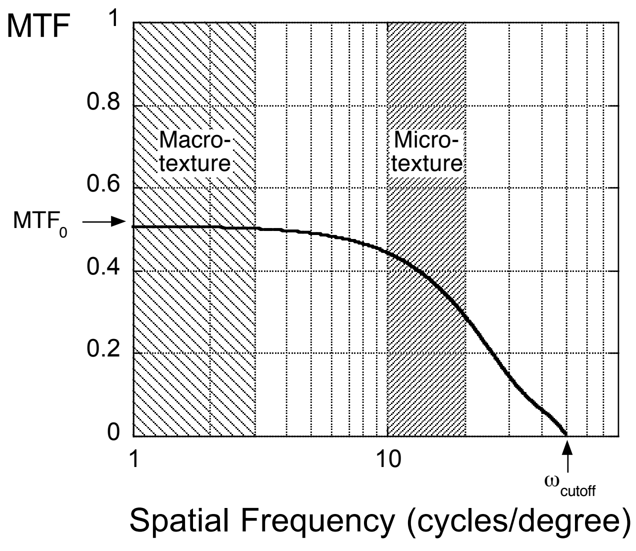

Fig. 4: Typical MTF with MTF_0 and ω_{cutoff} labeled. Representative macro- and micro-texture ranges are also depicted.

Fig. 5: Locations utilized for MTF extraction over a broad field of view.

defined by high spatial frequencies, e.g., in the 10–20 cycles/degree range. For example, in the generic MTF curve shown in Fig. 4, $\overline{\mathrm{MTF}}_{\mathrm{macro}} = 0.5$ and $\overline{\mathrm{MTF}}_{\mathrm{micro}} = 0.37$. The spatial frequency ranges in the example are representative of human perception thresholds [9].

If it is possible to arrange multiple optical targets over the region of interest, as in Fig. 5, the analysis of the spatial dependency of the MTF can also be simplified. First, it is reasonable to assume that all optical paths emanate from a single point, such as a videocamera, as in Fig. 5, or the pilot’s eye. If the MTF is extracted at points all at the same height from the ground, then $\overline{\mathrm{MTF}}_{\mathrm{macro}}$ can be displayed as a contour plot (similarly for $\overline{\mathrm{MTF}}_{\mathrm{micro}}$). The time dependency of the MTF can then be displayed by using the contour plots at each instant in time as the frame of an animation.

Further research is needed to determine whether this is the most useful representation of the MTF for handling qualities applications, i.e., that which best correlates with pilot behavior in brownout and other DVE conditions.

RESULTS

Measurements in Clear Air

Figure 6 shows the grayscale levels for the edges labeled (a)–(f) in Fig. 3. The measurements are all in clear air, with no brownout cloud. The sharp black-to-white edge (a) shows well-defined grayscale values for the black and the white parts, and a clear, sharp transition. In the case of the“black-to-sand” edge (b), sufficient contrast exists to maintain a clearly defined edge region, though the grayscale response of the ground region is much noisier than for the light region of target (a). The edge region is difficult to distinguish for the “white-to-sand” edge (c). Although the edge can be inferred from the change in scatter of the grayscale response, there is not enough contrast to clearly define a suitable edge for MTF extraction. Location (d), the small “edge strip” provides a very sharp edge for MTF calculation, in fact, sharper than for edge (a). This is because the edge strips were made of high-quality poster material mounted to wooden boards–the other resolution targets were painted wood, see Fig. 7, and had been exposed to the elements, including sand, for less time than the other resolution targets. Location (e), a sandbag with a strip of black tape, does not provide a clear edge because of the large variation in grayscale response for both the tape and sandbag. The grayscale levels for location (f), a cylinder with black and white segments, clearly display the effect of the curvature of the cylinder. The edge response takes on the appearance of

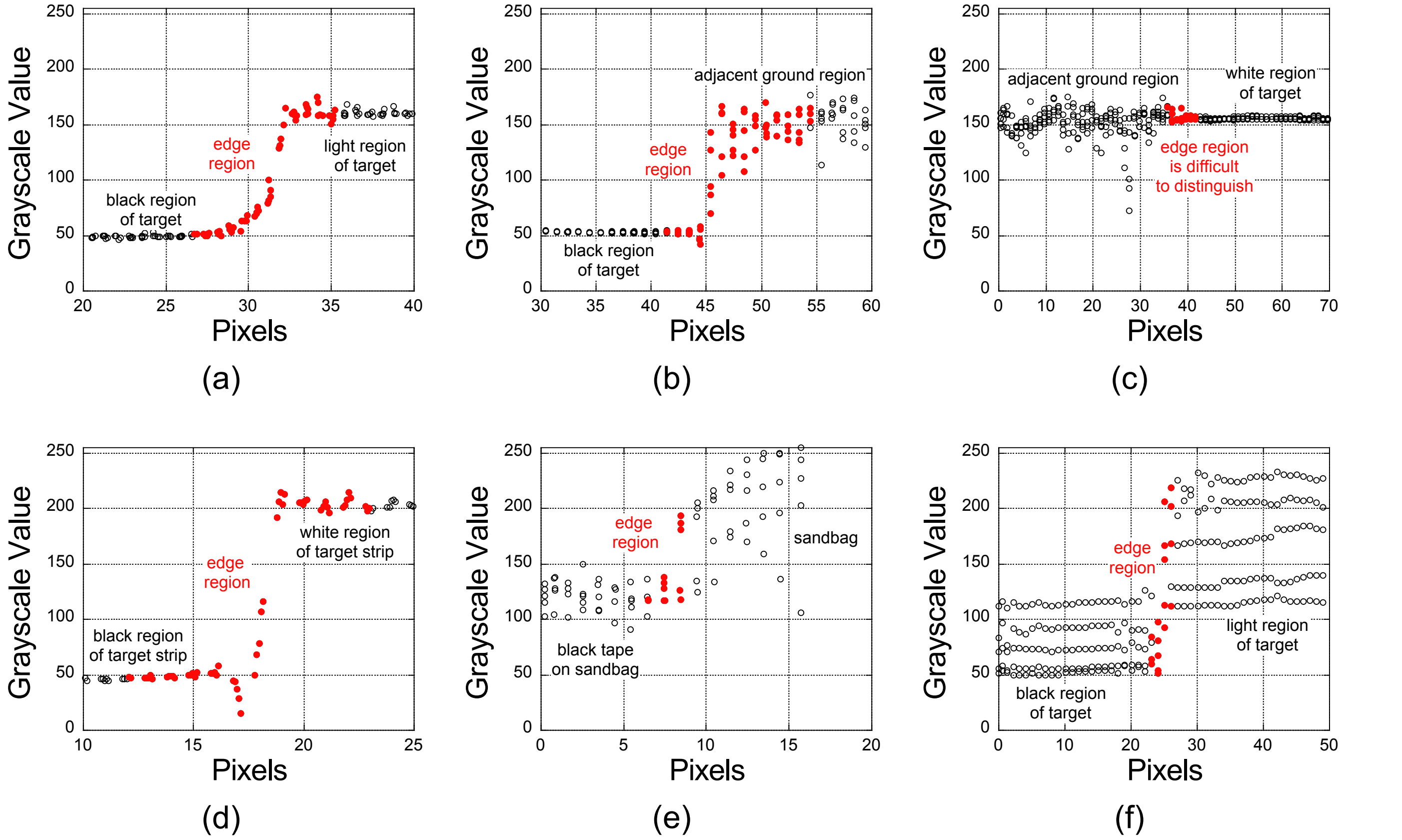

Fig. 6: Grayscale levels for optical edges at locations (a)–(f) in Fig. 3.

five step functions that are displaced in the y-direction. Each of these step functions represents a sample along one of five parallel lines, which, in the case of location (f), corresponds to one of five levels of shadow. The magnitude of the contrast varies significantly for each of these five levels. The magnitude of the contrast along the least responsive sampling line is approximately 60 grayscale levels (about 25% of the maximum contrast for 8-bit grayscale), while the magnitude of contrast along the most responsive sampling line is approximately 120–30 grayscale levels (about 50% of the maximum contrast for 8-bit grayscale).

The MTFs for each of the transitions of Fig. 6 are shown in Fig. 8. The baseline MTF at location (a) is consistent with prior work [7,8] in its overall magnitude and spatial frequency cutoff. Despite the noticeable scatter in the grayscale values of the black-to-sand edge (b), the high contrast between the black and the sand portions was sufficient for a successful MTF extraction, of comparable quality to the baseline. Likewise, the MTF was successfully calculated for location (d). The high contrast between the black and white segments of the edge strip resulted in an MTF of greater magnitude than the baseline and a wider bandwidth. The MTF at location (f) exhibited a very high bandwidth due to the sharp edge region, however the overall magnitude was significantly lower than the baseline due to the reduced contrast caused by the shadow. This confirms prior findings that indicated the presence of curvature can be problematic for MTF calculation [8]. Because the edge regions could not reliably be distinguished at locations (c) and (e), MTF calculations were not possible.

Measurements in Brownout Conditions

Figure 9 shows results for brownout conditions, extracted from the array of optical targets shown in Fig. 5. The 4 pictures in the left column, (a)–(d), refer to four successive instants of the evolution of the brownout cloud: in Fig. 9(a), the cloud is still outside the target field, though it is forming to the right. In Figs. 9(b)–(d), the cloud is progressively dissipating. A black-to-white edge was selected at the same location on

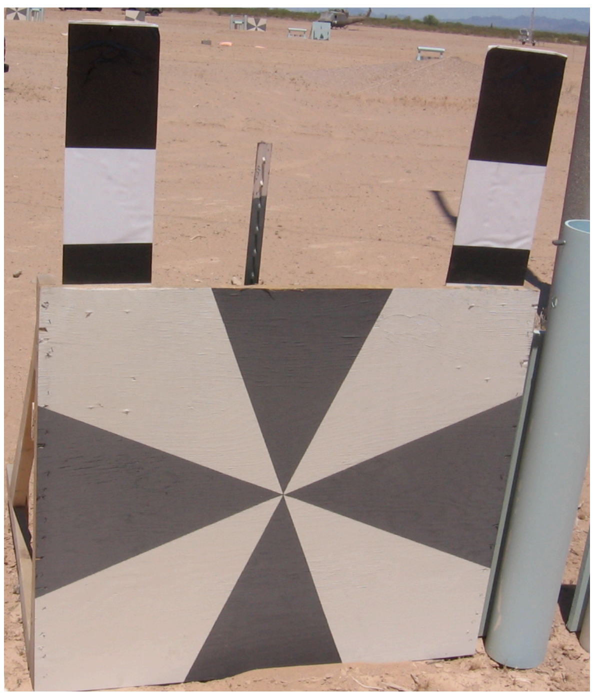

Fig. 7: Detailed view of the edge strips and optical target.

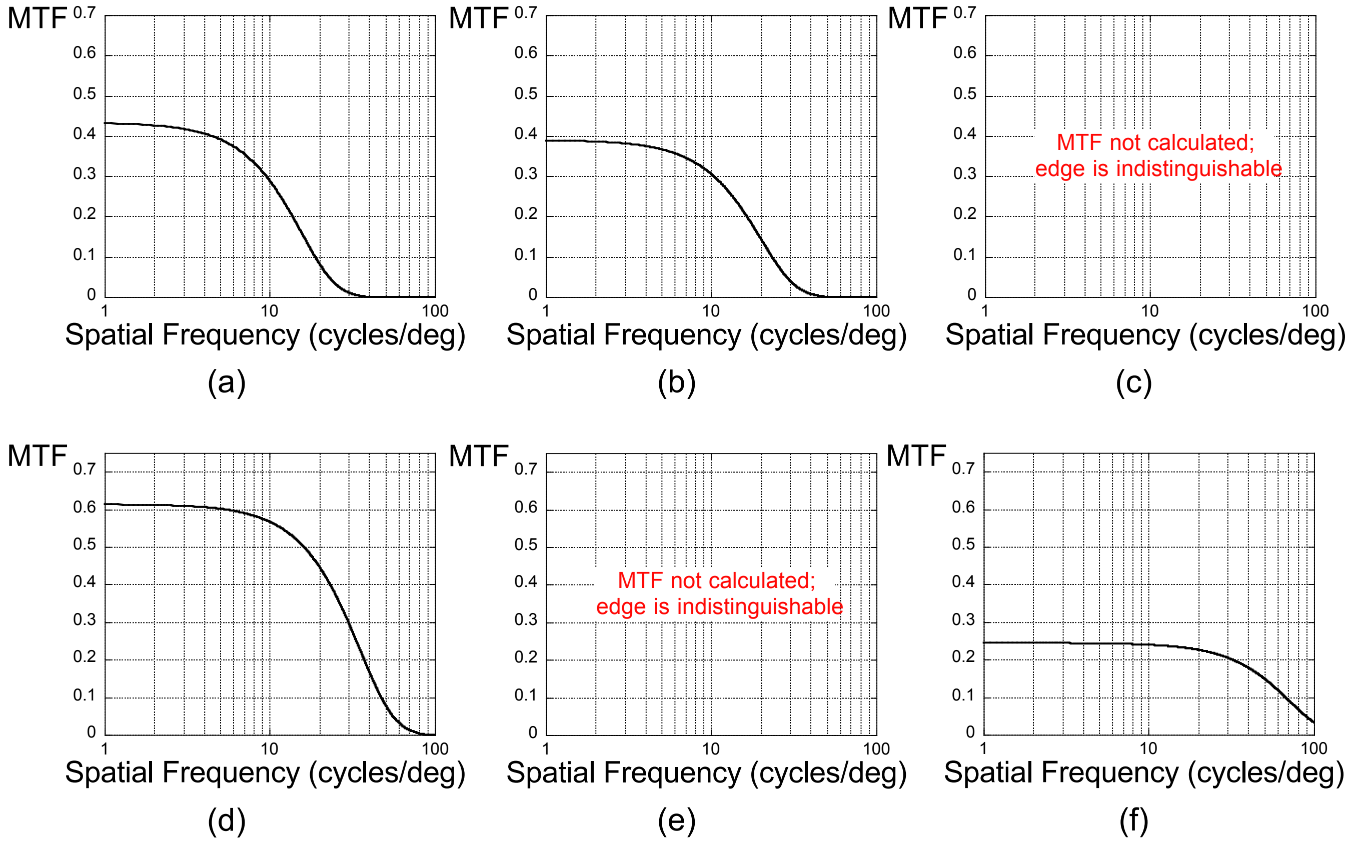

Fig. 8: MTFs for locations (a)–(f) in Fig. 3.

each of the 11 optical targets, similar to location (a) in Fig. 3, and the MTF was extracted across the edge at that location.

Next, the mean macro-texture MTF, $\overline{\mathrm{MTF}}_{\mathrm{macro}}$, was calculated using Eq. (5) for each of the 11 MTFs, and at each of the 4 time points. Each of the pictures in the center column, Figs. 9(e)–(h), is the same as the corresponding picture in the left column, but also contains a contour plot of the 11 values of $\overline{\mathrm{MTF}}_{\mathrm{macro}}$. Constant contours can be interpreted as lines of equal degradation of macro-texture visual cues. Before the brownout cloud engulfs the targets, Fig. 9(e), $\overline{\mathrm{MTF}}_{\mathrm{macro}} \geq 0.1$ over the visual field. As the cloud obscures the field of optical targets, $\overline{\mathrm{MTF}}_{\mathrm{macro}}$ tends rapidly towards zero, indicating that no macro-texture cues could be seen through the cloud. In Fig. 9(f) the cloud is beginning to dissipate. For the target closest to the videocamera, $\overline{\mathrm{MTF}}_{\mathrm{macro}} \approx 0.05$, and the visual degradation increases (i.e., $\overline{\mathrm{MTF}}_{\mathrm{macro}}$ decreases) moving away from the camera. In Figs. 9(g) and (h) the cloud continues to dissipate, and visibility continues to increase. The higher visibility for the targets closet to the camera is due to the fact that the optical depth, a measure of the integrated particle density over an optical path, is obviously lower for the closer than for the more distant targets.

Finally, the contour plots in the right column, Figs. 9(i)–(l), show the same information, only for $\overline{\mathrm{MTF}}_{\mathrm{micro}}$. The micro-texture MTF is clearly lower than the macro-texture MTF at all time instants, when the cloud is present. This quantifies the intuitively-known fact that brownout clouds obscure small details on the ground before they obscure large objects. At these, higher, spatial frequency scales, the characteristics of the complete imaging system (i.e., the camera, the atmosphere, etc.) may also play a role, as the range of spatial frequencies utilized in $\overline{\mathrm{MTF}}_{\mathrm{micro}}$ are close to the cutoff frequency of the system.

A similar approach can be utilized to interpret the variation of MTF values in time. In this case, only two optical paths from the vantage point in Fig. 3 are examined. Figure 10(a) depicts those two optical paths, which terminated at black-to-white transitions in the near- and far-field optical targets. Figure 10(b) and (c) provide the same FOV at 0.75 and 1.5 seconds later, respectively. Video footage was recorded at a 30 frames-per-second rate, and the MTFs along optical paths A and B were calculated for each image. From each of these MTFs, $\overline{\mathrm{MTF}}_{\mathrm{macro}}$ and $\overline{\mathrm{MTF}}_{\mathrm{micro}}$ were computed and they are plotted as functions of time in Fig. 11. Both Fig. 11(a) and (b) show some minor variations in $\overline{\mathrm{MTF}}$ before a sudden and sharp decrease over a few tenths of a second. This drop occurs first for optical path B because the brownout cloud develops from right to left across the image.

Additional Considerations

The methodology described in the previous sections could also be considered as a "proof of concept", for the true brownout MTF calculations from the cockpit during a landing maneuver that would be of interest for handling qualities studies. In this case, the video camera would be mounted in the cockpit, looking outside, rather than being fixed outside the cloud, looking in. The cloud would thus develop in front of the helicopter and engulf it, rather than developing in the field of view from right to left. The measurement and processing techniques, however, would be identical to those presented herein.

The present work also suggests that ground level MTF measurements during landing are possible, and could be performed using small targets that consist of a narrow strip with a black/white edge. Figure 6 indicates that the strips would only

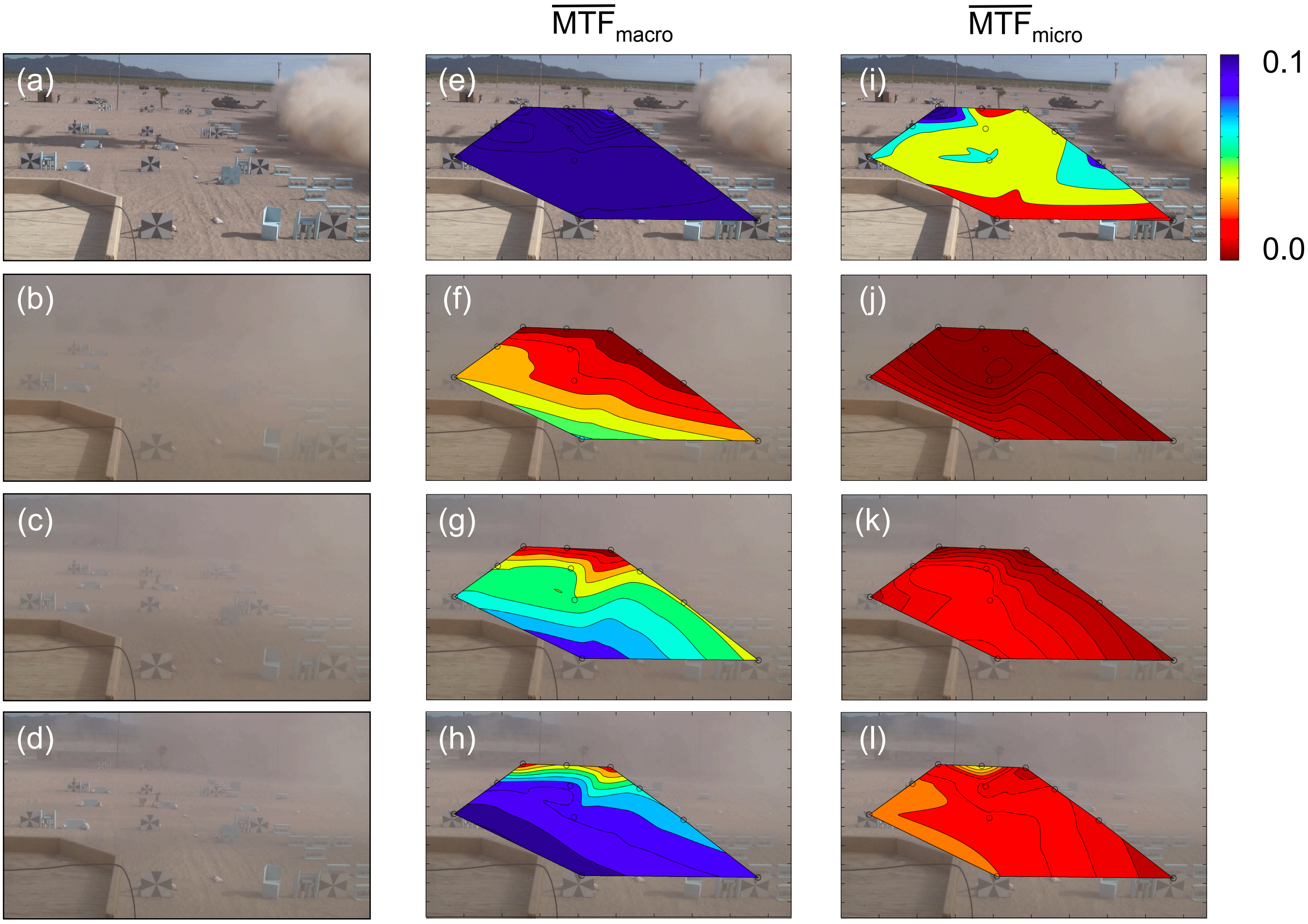

Fig. 9: Contour plots of mean MTF over a broad FOV for low and high spatial frequencies (center and right columns, respectively).

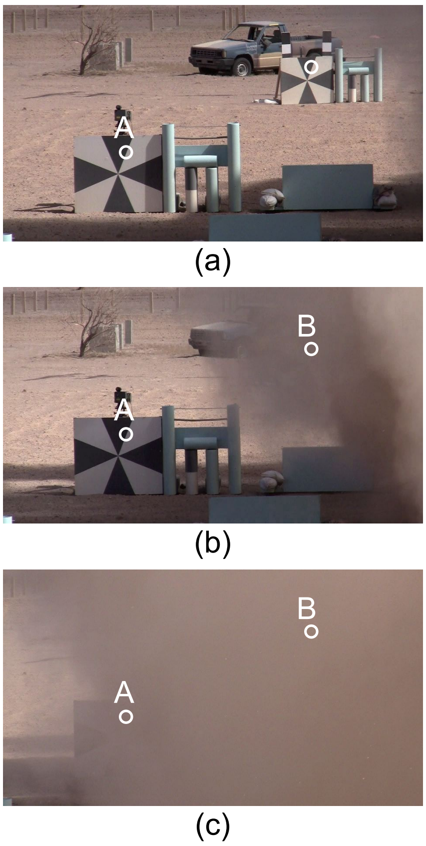

Fig. 10: Snapshots corresponding to Fig. 11 at (a) 0 sec, (b) 0.75 sec, and (c) 1.5 sec.

have to be large enough to accommodate a sampling region within the image frame that is about 20 pixels wide on the video camera sensor and approximately 10 pixels in height. Because of their small size, it should be possible to place and safely secure these strips in the landing area.

The behavior of a pilot in brownout conditions is determined by many mechanisms, some not fully understood. Visual inputs are part of the picture, but vestibular and proprioceptive inputs also play a role. Moreover, contrast and texture are not the only visual drivers of pilot behavior. For example, the sediment motion in a brownout cloud may create the illusion of motion in a certain direction, when the helicopter is actually not moving or is even moving in the opposite direction. Therefore, the information that MTF measurements can provide is only a piece of a complex puzzle. Nevertheless, quantifying contrast and texture is likely to be very important both for fundamental research in handling qualities, and for practical applications such as an objective, rather than pilot-centered, assessment of DVE.

CONCLUSIONS

The paper addressed the problem of measuring the Modulation Transfer Function (MTF) at or near the ground level of a sandy soil area. Because the MTF provides quantitative information on loss of visual contrast and texture, it could be useful to quantify the loss of visual cues in brownout conditions.

The results presented in this paper indicate that:

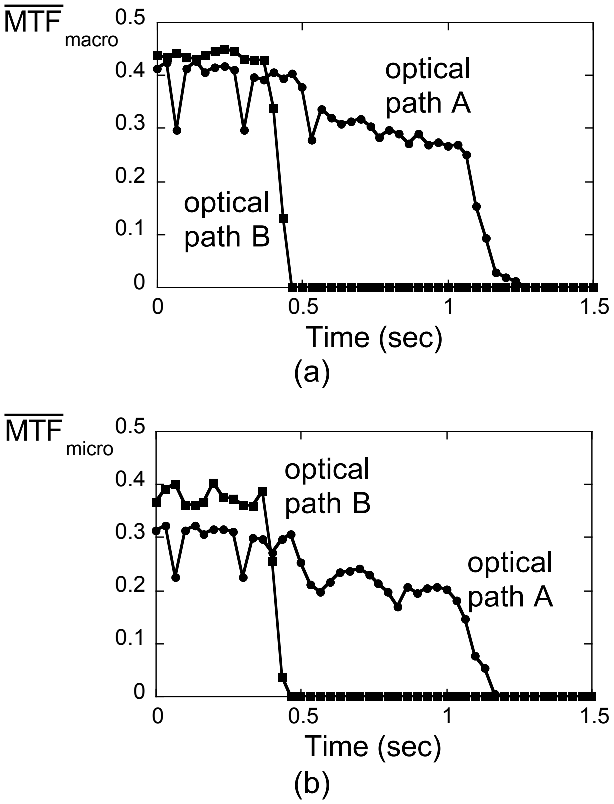

Fig. 11: (a) $\overline{\mathbf{MTF}}_{\mathbf{macro}}$ and (b) $\overline{\mathbf{MTF}}_{\mathbf{micro}}$ vs. time for a hover taxi maneuver.

1. It is possible to measure the Modulation Transfer Function of a brownout cloud at or near ground level, by analyzing the black/white transitions of an edge on an optical target. Black/sand transitions are also suitable, but less precise.

2. It is possible to interpret a large number of MTF calculations over a range of space and time in ways that succinctly quantify the degradation of visual cues caused by a the brownout cloud. At a given instant in time it is possible to compose contour plots that describe the loss of visibility over wide regions (e.g., an entire landing area). Similarly, the temporal variation in visibility degradation due to the brownout cloud can be plotted to gain a more complete understanding of the brownout problem. The intuitively known fact that small details and ground texture are obscured before larger objects, i.e., that the sediment cloud acts as an optical low-pass filter, is correctly captured quantitatively.

3. Because the physical size of the optical targets needed for MTF calculations is very small, it is possible that multiple targets could be safely placed in the immediate vicinity of the landing area, which would allow MTF measurements along paths from the pilot's eyes to points in the landing area. These measurements would quantify the degradation of the visual cues available to the pilot, and improve our fundamental understanding of the effects of brownout on handling qualities.

APPENDIX A: CONSIDERATIONS FOR MTF FLIGHT TEST PLANNING

The results presented in the paper indicate that future testing may be possible by which the MTF of a brownout cloud can be measured from the pilot's station, looking outward (this has not been accomplished previously due to safety of flight concerns), using small black-and-white strips safely anchored on the ground. The results also point to some initial guidelines to perform such tests:

1. **Select a suitable camera.** Ensuring that the camera has sufficient resolution can be done as follows. Recalling that the "cutoff frequency" for a camera with pixel width a is $\omega = (2a)^{-1}$, a camera with a field of view (FOV) of x by y degrees and a resolution of i by j pixels will have a pixel width of approximately $a \approx x/i \approx y/j$. The cutoff frequency of the camera is then $\omega \approx (2x/i)^{-1} \approx (2y/j)^{-1}$. For example, if a camera has a FOV of 30° laterally, and each frame contains 1920 pixels laterally,
$$\omega \approx \left(\frac{2\times 30^\circ}{1920\text{ p}}\right)^{-1} \approx 32 \text{ cycles per degree.} \tag{7}$$
Note that an *optical* zoom effectively decreases the FOV while maintaining the same number of pixels (leading to finer resolution), whereas a *digital* zoom, decreases the number of pixels (i.e., it simply crops the actual image), so it results in no improvements in resolution. Care must be exercised around the use of auto-focus features. For a moving target and stationary camera, the use of the auto-focus may be essential for maintaining a clear image. For a stationary target and stationary camera, auto-focus features may best be turned off. For a moving camera and stationary target (i.e., for a camera that is mounted on a helicopter), simple "risk-reduction" tests should be conducted prior to testing (for example, by placing the camera in a moving car and assessing the impact of the auto-focus feature).

2. **Fabricate optical targets that are suitably sized.** The present study suggests that, in order to achieve reliable results using the edge response method, the region of the optical target that is sampled ought to take up at least 20×10 pixels of the frame. To avoid sampling near the edges of the target, it is recommended that the target itself be designed to be at least 2–3 times this size. In order to determine the actual dimensions of the optical target, the maximum distance from the target for which measurements will be extracted must be identified. For a target of width w, with its endpoints relative to the observer given by $\underline{v}_1$ and $\underline{v}_2$ (see Fig. 12), the angle subtended in the observer's FOV can be approximated using the law of cosines:
$$\alpha = \cos^{-1}\left[\frac{w^2 - |\underline{v}_1|^2 - |\underline{v}_2|^2}{-2|\underline{v}_1||\underline{v}_2|}\right]. \tag{8}$$
The same formulation can be used to determine the angle subtended in height, α_h. Again, for a camera with a FOV of x by y degrees and a resolution of i by j pixels, the width and height of the optical target in the frame (in pixels) are approximately:
$$w_{\text{pixels}} = i \times \frac{\alpha}{x} \tag{9}$$
$$h_{\text{pixels}} = j \times \frac{\alpha_h}{y}. \tag{10}$$
For example, consider a camera with a FOV of approximately $30^\circ \times 17^\circ$, with each frame containing $1920 \times$

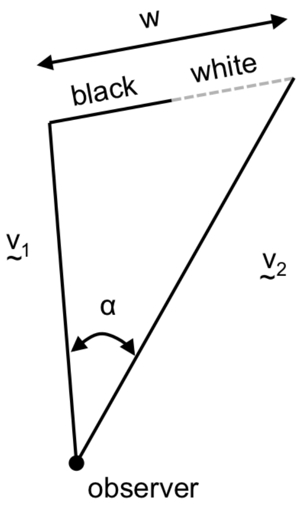

Fig. 12: Schematic diagram of an optical target in an observer's FOV.

1080 pixels. It is desirable for the size of the target in the frame to be approximately 60×30 pixels. In order for reliable MTF extraction, the width and height of the target (for a maximum distance from the observer given by $\underset{\sim}{v}_1$ and $\underset{\sim}{v}_2$) ought to subtend the angles

$$\alpha = \frac{\left(w_{\text{pixels}} \times x\right)}{i} = \frac{(60\text{p} \times 30^\circ)}{1920\text{p}} \approx 0.94^\circ \quad (11)$$

$$\alpha_h = \frac{\left(h_{\text{pixels}} \times y\right)}{j} = \frac{(30\text{p} \times 17^\circ)}{1080\text{p}} \approx 0.47^\circ \quad (12)$$

3. **Plan the arrangement of optical targets carefully.**

   Shadows Shadows will reduce the contrast of a typical optical test pattern, and intermittent shadows will increase the variance of the MTF_0 measurements.

   Multiple targets If multiple targets are in the FOV of a single camera, it is possible that the results will experience some noticeable variation—particularly if the camera has an auto-focus feature that is being utilized. If at all possible, the use of multiple cameras with smaller FOVs is preferred over the use of a single camera with a larger FOV.

   Edge orientation Results have suggested that near-horizontal and/or near-vertical edges in the image frame are preferable. These orientations lead to sharper edges due to the pixel arrangements within the image.

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