# 120 HERTZ – THE NEW 60 FOR FLIGHT SIMULATION?

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## *ABSTRACT*

*Recent advances in technology have led to the development of out-the-window (OTW) scene generators with unprecedented levels of realism; attainable levels of resolution, database detail, color, contrast, and luminance have significantly increased for flight simulation applications.*

*These aforementioned characteristics describe the static qualities of the image. These characteristics, and other factors, also affect the dynamic qualities of not only the out-the-window scene, but also the overall performance of the simulator. Aspects of simulator performance affected by update rate will be discussed.*


## INTRODUCTION

Currently, the majority of the industry has adopted 60 Hz update rates as a standard, yielding a good compromise between image quality and scene complexity.

One might wonder why we would want to improve on this, given that we enjoy cinema, which is has an effective update rate of 24 Hz[1], and many of us *were once* very satisfied with traditional interlaced television, updating only half frames at 60 Hz. Current television content is typically delivered at 30 to 60 Hz.

There is a significant difference between television/cinema content and real-time out-the-window visual simulation imagery. Cinema and television imagery is presented in a passive setting in which the viewer does not interact with the display. This passive playback of the image content allows television/cinema content to be processed significantly to optimize viewing quality. Even for live video feed, significant processing can be done, potentially introducing several seconds of delay (latency, transport delay). This delay is not perceived by the viewer because of the passive nature of viewing, as long as the update rate is maintained.

Cinema and television imagery obtained with traditional video and film cameras typically will have some inherent blur when the scene is in motion, because of the effective exposure time. The recent advent of 4k[2] digital cinema cameras shooting at 60 Hz has done little to change this. Even non-real-time, high quality rendered computer graphics (i.e. Pixar, Dreamworks) simulate camera blur for content with motion.

Unlike cinema and television, real-time flight simulation imagery must be *generated* and *displayed* in *real-time* with *minimum latency*, in order to have good closed-loop control characteristics. Additionally, real-time computer generated images are a snapshot in time; no blur is introduced in the rendering process.

This paper focuses specifically on the benefits of increased update rate for the display of real-time, computer-generated imagery, intended for interactive/piloted simulation. In this type of application, increasing update rate can improve closed-loop image motion perception and closed-loop control in three ways:

1) Reduction in motion-related artifacts
2) Reduction in closed-loop system latency
3) Reduction in visible flicker

The terms update rate, and related terms refresh rate and frame rate, are defined as follows:

[1] Frames recorded at 24Hz are repeated three times, and shown at a refresh rate of 72 Hz (flicker would be evident at 24 Hz).

[2] In cinema, the terms 4k and 2k refer to the width in pixels (approximately) of the image content and/or display.

Refresh Rate – The rate at which an image is redrawn on the screen/display (function of the display).

Frame Rate – The rate at which image content is created (function of the image generator).

Update Rate – The rate at which new images are displayed on a display screen (dependent on both image generator and display).

The benefits of increasing update rate discussed here are specific to the *definition* of update rate above – not only does the display have to refresh at the update rate, but the image generator needs to be capable of providing new image content (frames) at the update rate as well.

The potential benefits of increased update rate are related to the human interaction with the display and simulation system. Motion-related artifacts are associated with the coupling of human visual perception with a temporally sampled, rather than continuous, image. Closed-loop system latency has long been recognized as a parameter that needs to be minimized to accomplish closed-loop control in flight simulators. Lastly, flicker is a characteristic that will become noticeable under certain circumstances, with the saliency of flicker varying among individuals. Each of these will be addressed individually in the next sections.

## MOTION-RELATED VISUAL ARTIFACTS

Motion-related visual artifacts are defined as characteristics or features that are visible in a temporally sampled and displayed visual scene, which would not be present in a naturally viewed scene.

Two motion-related visual artifacts are motion-induced blur (MIB) and spatio-temporal aliasing (STA). The characteristics of these artifacts will be discussed in the following section, including discussion of methods to reduce the saliency of these artifacts and the effect of update rate.

### Motion-Induced Blur (MIB)

Motion-induced blur is an interaction between the viewers' pursuit eye-movements[3] and the display. This topic is discussed in more detail in Sweet & Hebert (2007). MIB occurs with displays featuring a long **hold-time** (i.e., the amount of time a pixel is illuminated relative to the display's refresh rate). Liquid Crystal on Silicon (LCoS), Liquid Crystal Displays (LCD) and Digital Light Processing (DLP) displays achieve high brightness (relative to cathode ray tube, or CRT, displays) by illuminating each pixel for nearly the entire refresh period. Figure 1 shows the luminance profile of an LCD and a CRT display.

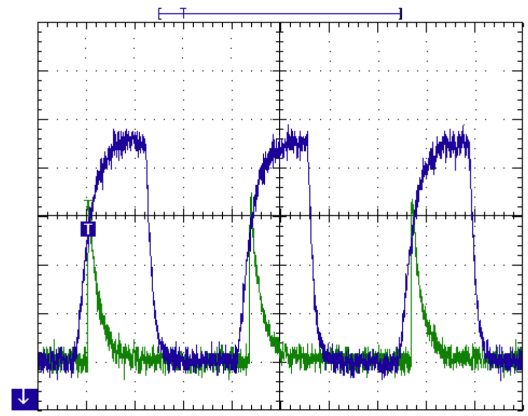
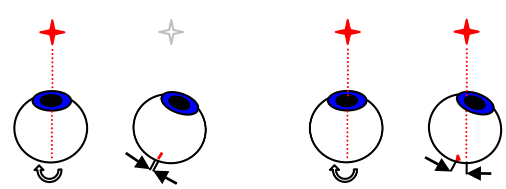


Figure 1 – Overlay of CRT response (green) to the LCoS response (blue) to a flashing square stimulus of 1/60sec on, 1/60sec off. (From Sweet et. al., 2007).

Long hold time displays, when viewed with pursuit eye movements, produce the perceptual outcome of motion-induced blur. The eye is moving continuously throughout the frame, while the displayed image is stationary during the frame. The result is that the image blurs on the retina of the moving eye (Figure 2).



(a) (b)

Figure 2 – As shown in (a), the relatively brief illumination of the CRT pixel simulates a small visual angle of the retina (between the arrows) even when the eyes are engaged in smooth pursuit eye movements. The long illumination of the LCD, LCoS, or DLP pixel stimulates a large portion of the retina (shown between the arrows) when the eyes are moving, resulting in blur. (From Sweet et. al., 2007).

[3] Pursuit eye movements are continuous, smooth movements of the eye that occur when tracking a moving (or apparently moving!) object.

One commonly used method to decrease motion-induced blur is to decrease the portion of a frame that the pixels are illuminated (hold-time). Specific implementations vary from mechanical shuttering mechanisms, LCD shuttering, black frame insertion, and light intensity modulation (most major projection vendors have some method to reduce motion-induced blur). These methods result in decreased display brightness; reducing the hold-time to half of the frame will decrease the brightness by half. Additionally, reduction in hold-time can make flicker become visible, or more apparent.

The **magnitude** of MIB artifacts is relatively easy to predict – the blur can be approximated by the motion rate divided by the frame time – this gives us how far the eye moved during the frame, which is the extent of the blur.

For a 60 Hz update rate display, and, for example, image motion of 12 deg/sec, the blur experienced would be (12 deg/sec)/(60 cycles/sec) or 0.2 degrees (12 arcmin[4]). For a hypothetical simulator with 3.0 arcmin/pixel, this would equate to a blur of 4.0 pixels, making it difficult to make out any high-resolution features for displays resolution (and image complexity) of less than 4.0 pixels, even at this modest image motion.

***Increasing update rate decreases motion-induced blur, while retaining display brightness.***

<u>Spatio-Temporal Aliasing (STA)</u>

Strictly speaking, STA is considered to be present when a sampled image is distinguishable from a continuous image (this is discussed in more detail in Sweet, Stone, Liston, and Hebert, 2008). Of course, there is a large qualitative difference in sampling that is barely distinguishable from continuous motion, and sampling that does not even form a good perception of motion.

Many studies of visual motion perception have used point stimuli – a single point of light that is presented at different locations in time. Such a sampled image sequence begins to be perceived as motion at update rates in the range of 15 to 20 Hz; the quality of the motion is related to the time and distance intervals between images (Sperling, 1976).

[4] An arc-minute (arcmin) is 1/60th of a degree. An arc-second (arcsec) is 1/60th of an arc-minute.

Sperling (1976) noted that small time intervals, and small distance intervals, resulted in the best perception of motion. The method used to define and display these intervals is shown in figure 3.

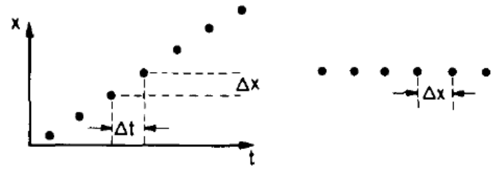



Figure 3 - ‘x’ refers to translation distance, ‘t’ refers to presentation time. Judgments of motion quality were made for varying levels of Δx and Δt. (From Sperling, 1976).

Subjective judgments of motion quality were made in a range from 0 (no motion) to 10 (apparently continuous motion). Comments regarding poor motion depiction/low ratings included ‘jerkiness’, ‘flicker’, ‘object turns on and off’. Rating contours from this reference are shown in figure 4.

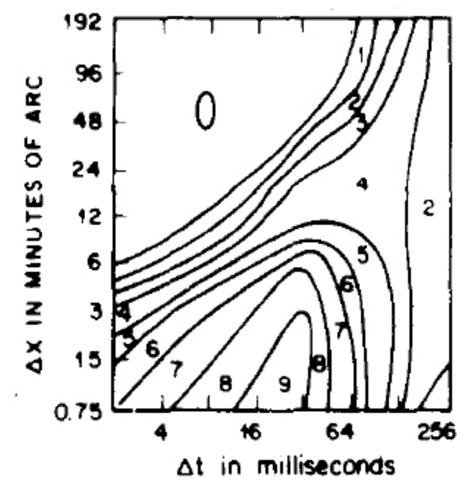



Figure 4 - Contours of motion quality, from 0 (no motion) to 10 (nearly continuous motion). (From Sperling, 1976).

As indicated previously, these results were obtained using ‘point’ stimuli. With the exception of aircraft at large distances, moving objects in simulated visual scenes tend to be more complex than point stimuli. The visibility of the sampling is actually related to the spatial frequency content of the image – in practical terms, how big the features in the image are. Thus, for a given image speed, STA will be more visible for a small feature than a large one. Watson, Ahumada & Farrell (1986) describe a simple method that can potentially be used to determine the threshold at which STA becomes visible as a function of spatial frequency content of an image (which can be lower than the image/display resolution).

The point at which sampled motion is barely distinguishable from continuous represents very good motion depiction. At the other end of the spectrum lays the potential that motion will not be readily apparent, or that the sampling produces significant visual artifacts (as indicated by the comments regarding poor motion depiction). One visible artifact that becomes readily apparent in undersampled motion is a doubling of the features in the image. This occurs when the image features move so far between frames that the eye briefly retains the image of both frames. This is akin to a 'double exposure'. When an image begins to break up in this manner, it can be very difficult to fixate on or track detailed image features that are aliasing significantly.

***Increasing update rate improves the perception of continuous motion, by reducing spatio-temporal aliasing artifacts. For a given update rate, increasing display resolutions will make spatio-temporal aliasing artifacts become more noticeable.***

## LATENCY

Closed-loop system latency is an important consideration in flight and other human-in-the-loop simulation applications. Depending on the sensitivity/agility of the control task, excessive amounts of latency can make a simulated vehicle unrealistic and sluggish at best, uncontrollable at worst. With head-mounted displays, latencies as in the range of 6-20 ms can be detected by the viewer (Ellis, Young, Adelstein, & Ehrlich, 1999; Ellis, Mania, Adelstein, & Hill, 2004). Fortunately, pilots are accustomed to somewhat more latency between making a control input and seeing the environment move than when they move their head. Some latency can be attributed to the vehicle dynamics, and even corrected in the modeling, but excessive latencies cannot be modeled around.

A typical simulator will have at least three major components: 1) a cockpit (i.e. control effectors, display panel, switches/breakers) 2) a host computer and 3) a visual system (consisting of an image generator and display). Minimization of latency requires close synchronization of the individual components, frequently accomplished by syncing each component to an external sync signal (traditionally referred to as house sync), or using one component to sync the rest (master system clock sync).

Information transfer between the components typically occurs at frame boundaries – the control is sampled, the host computer determines aircraft state, this determines viewing geometry to be passed to the image generator, then the image generator sends the image to the display. With most modern applications, the image generator and display are the 'slow' parts of this process. Controls frequently are sampled at much higher rates than the update rate (ensuring that the most recent information will be used for computations); likewise, with modern CPU capacities, host computers can typically cycle faster than the IG/Display.

***When update rate is increased, frame intervals decrease, and latencies that are associated specifically with frame intervals will be decreased.***

<u>The Impact of Modern Digital Displays and Graphics</u>

A potential issue in visual simulation systems requiring high update rates is the use of Digital Video connections such as DVI, HDMI or Display Port in combination with High-bandwidth Digital Content Protection (HDCP) compliant video equipment. HDCP is used to encrypt the video output signal from a video playback (e.g. Blu-ray disk player) or image generation source to the end display.

While HDCP was designed by Intel as part of the new Digital Visual Interface (DVI) standard when it was first introduced in 1999, it was not widely put into use until 2004 when it became part of the "Digital Output Protection Technology" and "Digital Broadcast Television Redistribution Control" Federal Communications Commission (FCC) rule 47 CFR 73.9002(b), and requested by the Motion Picture Association of America (MPAA) to eliminate the "analog hole" in video equipment, in order to thwart "video piracy." In particular the Demodulator Compliance Requirements insists that all HDTV demodulators must "listen" for the "broadcast flag" and that "no party shall sell or distribute in interstate commerce a Covered Demodulator Product that does not comply with the Demodulator

Compliance Requirements and Demodulator Robustness Requirements." According to the rule, hardware must "actively thwart" piracy. As such, beginning as early as 2005 video equipment manufactures were including HDCP compliancy in their hardware.

While HDCP should not affect most current simulation systems, the potential for added latency does exist for visualization and research. It appears that most HDCP compliant consumer equipment allows for up to a 100ms delay in the HDCP chain (transmitting hardware to receiving display) for encrypted video based on HDCP documentation (Revision 2.1 18 July, 2011). Even if the video being generated does not require encryption under the HDCP standard, the hardware manufactures have all adopted the standard to be compliant with the law. For this reason, virtually all consumer HD displays (even those claiming 240 Hz or better update rates) implement a video buffering and caching architecture that is suitable for viewing of movies and television programs. But in the case of real-time visual simulations, this added latency would be unacceptable.

In practice this means that the HDCP encryption check (HDCP locality check watchdog timer) can introduce 7ms of latency to verify that HDCP is not needed before allowing your generated image out of the transmitting (image generator) system. If HDCP compliancy is present on both transmitting hardware and receiving display, but not needed, then the acceptable delay can be as much as 14ms. For visual simulations (or even video games) running at 60 Hz or better, the minimum of a 7ms locality check added into the overhead of your existing system could be sufficient to cause a noticeable update delay.

At NASA we are evaluating a direct comparison of an older non-HDCP compliant graphics card, and a newer HDCP compliant graphics card (driving an identical 60 Hz OpenGL visualization from the same computer). The early results point to an added frame of delay when the video chain uses a digital video signal driven from a HDCP compliant video card versus driving the same signal from an older non-compliant card. When an HDCP compliant display was added at the receiving end of the video chain (across a digital video connection), then an additional 1 to 2 frames of delay were observed.

While further testing is needed to validate these results, and rule out other possible transport delay constraints, the issue of digital video using HDCP equipment, does loom as a possible performance issue for simulations, especially when we look at running systems at 120HZ update rates with newer hardware.

Savvy consumers are becoming aware of this problem with the current crop of modern home video game systems (e.g. PlayStation® 3, Microsoft Xbox 360). These newer game systems can run visuals at up to 60 Hz on "compliant" displays. When synchronizing game controller input with on-screen actions, game manufactures have been forced to introduce latency mitigation controls or input "fudge factor" settings that allow the player to tune the video game based on the apparent latency in their home entertainment system. Examples of this can be found in the popular video games Guitar Hero® and RockBand®.

***Newer display and graphics technologies have the potential to introduce additional latency, which can be mitigated in part by increasing update rate.***

## FLICKER

Aside from motion perception, we have another characteristic of temporal perception: flicker. The critical flicker frequency (CFF) is the threshold at which temporal modulation of luminance in a stimulus ceases be visible. This value varies as a function of mean luminance, eccentricity, and stimulus size (Hartmann, Lachenmayr, and Brettel, 1979). CFF peaks at approximately 30 degrees eccentricity; simulator visual systems with field-of-views greater than 30 degrees are likely to provide visual stimulation at this area of peak sensitivity. Likewise, stimulus size in a visual display is extremely large, maximizing the potential for visible flicker.

It is often accepted as common knowledge that CFF is approximately 60 Hz. However, this varies significantly with luminance, and there are large differences between individuals. Hartman et. al., (1979), determined CFF at approximately 30 deg periphery to be in the range of 50-60 Hz with a 70 cd/m2 (20.4 ftL) display, using a single subject. Bauer, Bonacker & Cavonius (1983) determined the CFF for 31 individuals for displays of 80, 160, and 320 cd/$m^2$ (23.3, 46.6, and 93.3 ftL) luminance. At 80 cd/m$^2$, they determined that in order to above the flicker threshold for 95% of the population, a frame rate of 87 Hz was necessary; 95 Hz was necessary for the 320 cd/m$^2$ display.

The temporal waveform of the illumination is also a factor that affects perception of flicker. In the field of illumination engineering, "flicker index" is used to assess potential for visible flicker (Illumination Engineering Society of North America, 2000). Flicker index is defined as the area of the illumination above the mean luminance, divided by the total area under the luminance curve. This index can go from 0 to 1.0, with low values associated with low flicker, high values with highly visible flicker. For a given frequency, it gives a good indicator of subjective flicker associated with the luminance waveform.

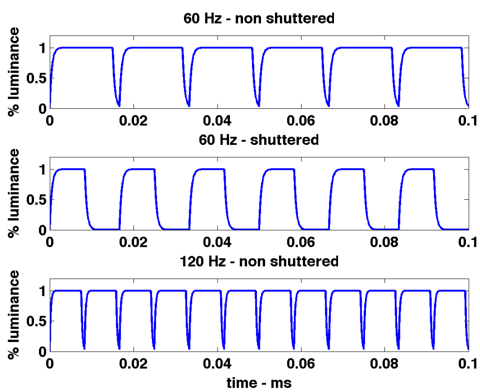



Figure 5 - Hypothetical temporal variance in luminance for 60 Hz non-shuttered (top), 60 Hz shuttered (middle), and 120 Hz non-shuttered (bottom). Calculated flicker index for the 60 Hz unshuttered case is 0.09, compared to 0.46 for the 60 Hz shuttered case. The 120 Hz case would not flicker because it is well above the frequency at which flicker can be detected.

As indicated in the previous section on MIB, the most common method used to reduce MIB is to shutter or modulate the illumination within a frame. With this significant modulation, flicker potentially will become visible when motion-blur reduction is enabled for at least a segment of the population (see figure 5). Specific methodologies for shuttering will produce different waveforms, and likely different levels of visible flicker.

***When update rate is increased, visible flicker is reduced. Update rates necessary to eliminate visible flicker in nearly all viewers depend on the luminance waveform and average display luminance.***

## DISCUSSION

Like most highly complex systems, the factors that affect performance and suitability of flight simulator visual systems are multidimensional.

There is a potential for mismatch between achievable static and dynamic resolutions in visual system design. The magnitude of both MIB and STA artifacts are a function of system resolution and image motion.

Figure 6 illustrates this potential mismatch. Motion-induced blur has been calculated as a function of image motion for three hold times: 16.7, 8.3, and 4.2 ms (equivalent to 60, 120, and 240 Hz non-shuttered operation). Potential system resolutions of 1, 2 and 4 arcmin/pixel are depicted with horizontal lines. MIB will not become visible until it exceeds the system resolution. For a system resolution of 6.0 arcmin/pixel, MIB does not become apparent until image motion exceeds 4.0 deg/sec. However, at a system resolution of 1.0 arcmin/pixel, MIB is present at extremely low image motions.

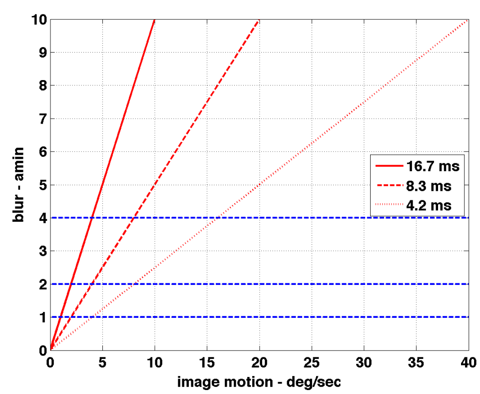



Figure 6 - Motion-induced blur is shown as a function of display resolution and image motion, for 16.7, 8.3, and 4.2 ms hold times. Lines at 1, 2, and 4 arcmin depict potential system resolutions.

Shuttering to prevent MIB will increase these thresholds at which blur becomes evident, through reduction of the hold time. As previously noted, shuttering will reduce display brightness, and at 60 Hz, has the potential to introduce visible flicker. Shuttering at 120 Hz would not introduce visible flicker because the base rate is well above CFF thresholds.

These calculations are based on system resolution, that is determined with very high-contrast test patterns. In practice, image content is not created at the limiting resolution of the display, nor is it composed of stark black/white content. However, image motion can be quite high; aircraft roll/pitch rates upwards of 60 deg/sec are common in fighter aircraft. Additionally, the human ability to track motion extends to relatively high levels of motion[5] (Stone, Beutter & Lorenceau, 2000; Stone, Beutter, Eckstein, and Liston, 2008), and we retain good visual acuity at high tracking rates[6] (Brown, 1972). While in practice, with realistic image content, the slopes of the lines in Figure 6 are likely to be less steep, MIB **will** become apparent at sufficient levels of image motion. A potential topic of further research should be to determine these practical thresholds for visibility of MIB.

While MIB is easily quantified as a function of image motion, the salience and impact of STA is less easily determined. As indicated previously, the severity of STA varies from good depiction of motion (but detection of sampling), to no motion detection at all. Little has been done to quantify/qualify the impact, likely because the effects will vary as a function of *task*, in addition to update rate, image resolution, and image motion. In a study of helicopter autorotation (Schroeder, Dearing, Sweet, Kaiser & Atencio, 2001), three levels of spatial resolution were used for ground texture pattern. It was found that when performing autorotations, that the medium, not highest, level of spatial resolution elicited the best task performance. This was attributed to the fact that at the highest spatial resolution, significant STA was visible in the helicopter 'chin' window, which is the primary visual reference during the autorotative flare (due to high pitch attitude). Additional research to better understand the relationship between simulated task performance and STA would be beneficial.

How high does update rate need to be? Studies of the effect of update rate using a laser display capable of 240 Hz (Winterbottom, Gaska, Geri & Sweet, 2008) showed that relative to 60 Hz, motion-induced artifacts were significantly diminished at 120 Hz, and were not visible at 240 Hz. However, although conducted at eye-limiting display resolution (1.0 arcmin/pixel), the image content was not eye-limiting, and it would be expected that even at 240 Hz, artifacts would become visible with increasing levels of image detail.

It should also be noted that while many consumer displays on the market today claim 120, 240 or even 480 Hz rates, these are typically refresh rates. Increase in the image frame rate is achieved through resampling the source video (originally at 30 or 60 Hz) and producing a new higher speed interpolated image sequence (and/or using black frame insertion.)[7] The exception would be consumer stereo 3D displays that update at 120 Hz using interleaved 60 Hz images.

High update rate television that is achieved with image interpolation should not be confused with higher end displays and visual systems that can fully address an ultra high definition image at rates up to 120 Hz. With increasing display refresh rates, higher update rates can be accomplished either by increasing the image generator frame rate, or using two image generator inputs multiplexed in time. Increasing frame rate on an image generator can limit the available detail (by limiting rendering time), but given that motion-induced artifacts become more visible with increasing resolution, this might be a good trade in some applications. We have demonstrated at NASA that emerging display

[5] Pursuit eye movements provide effective tracking up to about 40 degrees/sec; after that we start to do quick corrections to refocus the target, with effective tracking dropping off at approximately 60 deg/sec.

[6] While human visual acuity does degrade somewhat with image motion, the degradation is very small in comparison to motion-induced blur. Brown (1972) measured changes in human visual acuity as a function of both stimulus motion and contrast. He found that in general, visual acuity degraded linearly as a function of image motion; at contrast levels of 23%, visual acuity varied from 1.8 arcmin with no stimulus motion, to 6.0 arcmin at 80 deg/sec stimulus motion. At contrast levels of 36%, acuity varied from 1.5 arcmin to 4.5 arcmin from no image motion and 80 deg/sec, respectively.

[7] The resampling occurs within the display hardware/software; resampling methods are specific to the display manufacturer and typically proprietary.

systems can generate true 120 Hz 2K images on a single display. But, producing interactive visual simulations at resolutions larger than 2K with true update rates of 120 Hz or greater in a single display is challenging. Given rapid growth of graphics hardware and software capabilities, it is anticipated that in the near future, updating image content at 120 Hz from a single image generator will become more achievable.

## CONCLUSIONS

Considerations for update rate should include display resolution, level of detail, application and what depictions of motion are important. Significant scene motion is associated with rotational motions (pitch, yaw, roll), and significant object or feature movement can occur w/ flight near other aircraft/structures/ground as well, and quick object motion. Dynamic requirements escalate quickly with improving levels of resolution and detail, and can be easily mismatched.

Given the benefits of 120 Hz update rate visuals from the standpoint of *motion-induced blur and spatio-temporal aliasing, visibility of flicker, and reduced latency, trading resolution and/or scene detail for higher update rates might be preferential in some applications.*

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## AUTHOR BIOGRAPHIES

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