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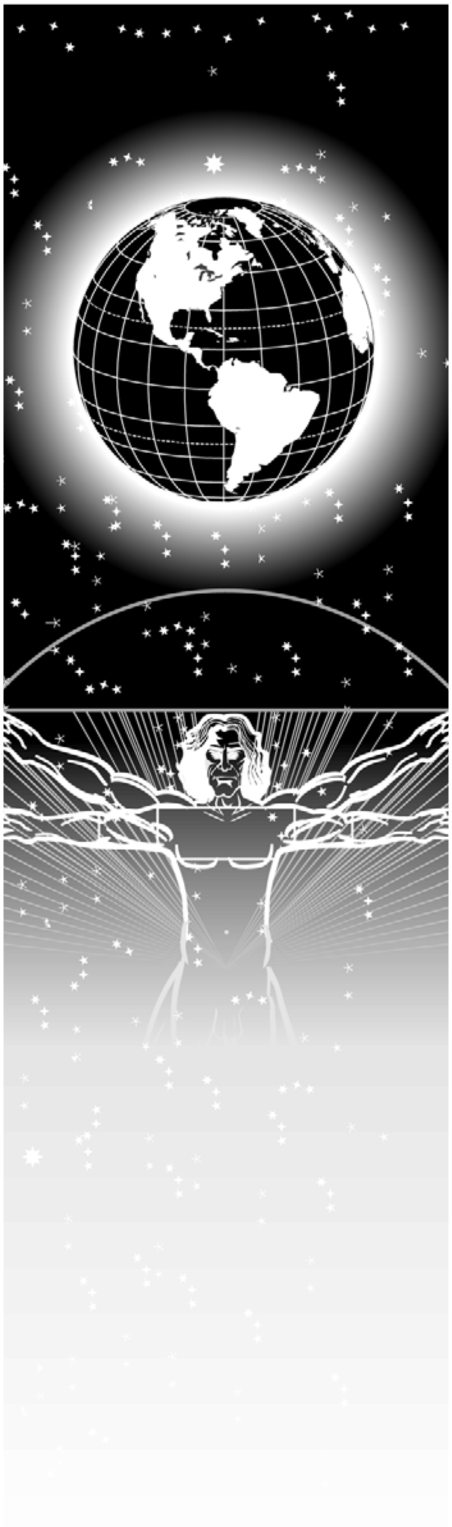

UNITED STATES AIR FORCE RESEARCH LABORATORY

NEXT-GENERATION FLIGHT SIMULATORS: IMAGE-UPDATE-RATE CONSIDERATIONS

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14. ABSTRACT
The level of detail in flight-simulator images depends upon the resolutions of the database, the image generator (IG), and the display. In response to the need for greater detail, resources are being devoted to increasing the spatial resolution of each of these system components. Next-generation flight-simulator visual systems will thus be capable of representing smaller environmental features and of representing a given feature at a greater distance. However, flight-simulator imagery is more than a sequence of static, spatial images. The visual system of a simulator creates three-dimensional space-time images, and the quality of these images depends on the temporal as well as the spatial characteristics of both the IG and the display. Here we discuss how the spatial resolutions of the database and the IG affect the temporal frequencies in an image and thus the extent of temporal aliasing likely with a standard, 60-Hz image-update rate. We also discuss how the spatial and temporal resolutions of a display system limit the spatiotemporal-frequency spectrum of the display image. We conclude with a brief description of some perceptual effects of temporal aliasing.

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Antialiased; Displays; Flight simulators; IG; Image generators; Image update rate; Next generation flight simulators; Spatial; Spatial resolution; Temporal; Temporal aliasing; Texel; Visual systems

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NEXT-GENERATION FLIGHT SIMULATORS: IMAGE-UPDATE-RATE CONSIDERATIONS

INTRODUCTION

In a flight simulator, the spatial resolutions of the database, the image generator (IG), and the display system all affect the sharpness and detail of the display image. The effects of a given component's resolution depend—in a variety of asymmetric ways—upon the resolutions of the other components. For example, an IG's digital representation of a given environmental location cannot contain more detail than is contained in the database, and the simulated distance at which a given detail can be represented is limited by the resolutions of the IG and the display.

In response to the need for greater detail in simulator imagery, resources are being devoted to increasing the resolutions of all the components in next-generation visual systems: Satellite images with one-meter resolution are being collected, and ultra-high resolution (~ 5000 pixel x 4000 pixel) displays and IGs are being developed. Flight simulator imagery is, however, more than a sequence of static spatial images. During simulated flight, the visual system creates a three-dimensional (two dimensions of space, one of time) space-time image that approximates the *continuous* changes in the spatial image that would result if the pilot were to actually fly through the synthetic environment. The quality of a space-time image thus depends upon the temporal as well as the spatial characteristics of a flight simulator's visual system.

Here we describe how (a) the content and resolution of the database, (b) the pixel density and antialiasing filters of the IG, and (c) the speed and altitude of the simulated flight jointly determine the temporal frequencies in the nominal space-time image internal to the IG (for the specific case of constant-altitude, constant-velocity, straight-and-level flight over flat terrain). We also discuss how the spatial and temporal resolutions of a display affect the spatiotemporal-frequency spectrum of the display image. Finally, we provide a brief description of the spatial and temporal characteristics of the human visual system (HVS) and of some findings regarding the perceptual effects of temporal aliasing.

COMPONENTS OF SPATIAL RESOLUTION

Database

A flight-simulator database defines the synthetic environment through which a pilot may fly. Ground and object surfaces are represented as polygon meshes. The chromoluminance pattern of a given polygonal surface is typically defined by a two-dimensional digital image called a "texture." A texture pattern can be created in a variety of ways. With current technology, it is often based on a photograph of some object or region of the world.

The individual elements (digital values) of a texture are called "texels." The resolution of a texture is defined by the texel "size"—that is, by the horizontal and vertical distance, in *environmental units* (e.g., meters), between adjacent elements in the texture pattern. In the past, a typical geospecific terrain texture had a resolution of 10 – 20 m. However, terrain textures with submeter resolution are becoming increasingly available. Moreover, with current IGs, the detail in a relatively low-resolution texture can be increased by modulating its values with those of a geotypical microtexture of arbitrarily high resolution.

Figure 1 depicts a 9.6-m and a 0.6-m resolution texture for a 153.6-m x 153.6-m terrain square. (To aid comparison, bilinear resampling was used to increase the size of the low-resolution image to that of the high-resolution image.) Note that the 0.6-m texture is sharper than, and contains features not represented in, the 9.6-m texture. Although a texture with a given resolution (e.g., 1 m) is not necessarily characterized by features that small, it is capable of representing such features.

(a) (b)

Figure 1. Effects of texture resolution on the representation of a 153.6-m by 153.6-m terrain square. The image in Figure 1a is based on a 16 x 16, 9.6 m/texel pattern; the image in Figure 1b is based on a 256 x 256, 0.6 m/texel pattern. Bilinear resampling was used to equate the sizes of the two images.

Image Generator

A perspective projection of a synthetic environment, onto the "view plane" internal to an IG, may be taken as a continuous space-time image. The IG samples this image in space and time to create a sequence of two-dimensional digital images. The spatial resolution, or pixel density, of an IG is defined by its horizontal and vertical sampling frequencies—that is by the size of a digital image, in pixels.

The continuous image, internal to the IG, is likely to be characterized by extremely (often infinitely) high spatial frequencies. If this image were sampled directly, at the infinitesimal points corresponding to the pixel array, any spatial frequencies higher than half the horizontal and vertical sampling (i.e., pixel) frequencies would be aliased—that is, they would appear in the display image as a frequency less than half the sampling rate.[1] To minimize spatial aliasing, IGs implement one or more antialiasing techniques. All such techniques serve to low-pass filter the continuous image, in *image units* (cycles/pixel), before it is sampled to create the pixel values. Although the filters differ in quality and none are ideal, here we make the simplifying assumption that an IG's antialiasing filters successfully remove all frequencies greater than half the pixel sampling rate and pass with minimal attenuation all frequencies less than half the sampling rate.

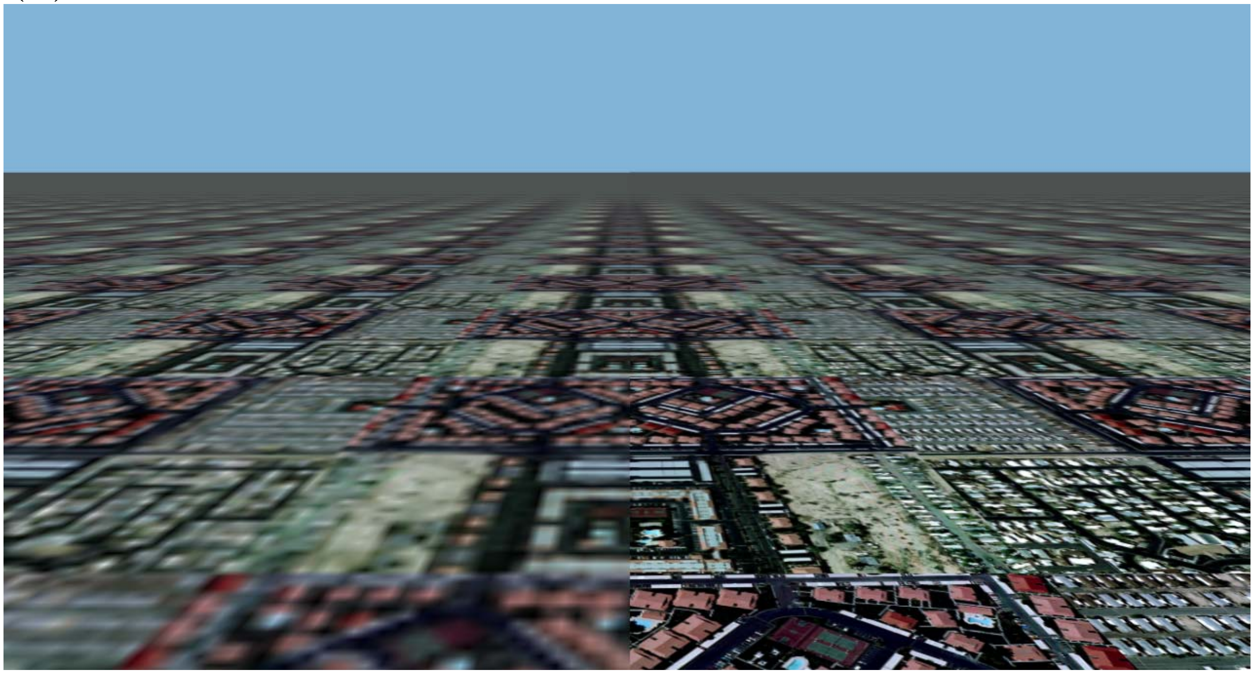
The projected size and shape of an environmental feature depends upon the distance and angle from which it is viewed. In a computer-generated image, then, the relationship between spatial frequency in cycles/m and spatial frequency in cycles/pixel varies within and between images generated by an IG of a particular resolution. Effects of texture resolution thus depend upon the simulated viewing distance, altitude, and terrain configuration. This dependency is illustrated in Figures 2a and 2b, which depict 40° vertical fields of view (with 30° below the viewpoint and the up-axis of the image perpendicular to the ground surface) of a synthetic environment consisting of a blue sky and a flat, textured terrain. The simulated altitude is 300 m (~1000 ft) in Figure 2a and 30 m (~100 ft) in Figure2b. Each half of the terrain was textured by "tiling" it with copies of a single texture pattern depicting a 614-m by 614-m region of the earth. The resolutions of the textures mapped to the left and right halves were 9.6 m and 0.6 m, respectively. To facilitate comparison, the high-resolution texture was "flipped" horizontally before it was mapped.

Note that, for both altitudes, the nearest visible terrain is sharper and contains more features when the texture resolution is higher. Similarly, for both altitudes, as the simulated distance along the ground increases, the effects of texture resolution decrease; on the distant terrain, the high- and low-resolution textures appear identical. Note also that the proportion of the image showing a texture-resolution effect is greater for an altitude of 30 m than for an altitude of 300 m.[2]

The larger the number of meters subtended by a pixel, the lower the antialiasing filter's cutoff frequency (in cycles/m), the lower the texture resolution that can be represented, and the larger the number of meters represented by a given pixel. For a given view of a synthetic environment, then, the higher the pixel density, the higher the texture resolution (and thus the greater the environmental detail) that can be represented at a given distance and the greater the distance at which a given texture resolution can be represented.

[1] For this statement to be consistently true, the display system must pass all spatial frequencies up to half the sampling rate.
[2] Although neither the differences among nor the imperfections of various antialiasing techniques are considered here, the images presented in Figure 2 were affected by the resolution and filters of the IG used to generate them. They were also affected by the resolutions and filters used to resample them for the present document.

(2a)



(2b)

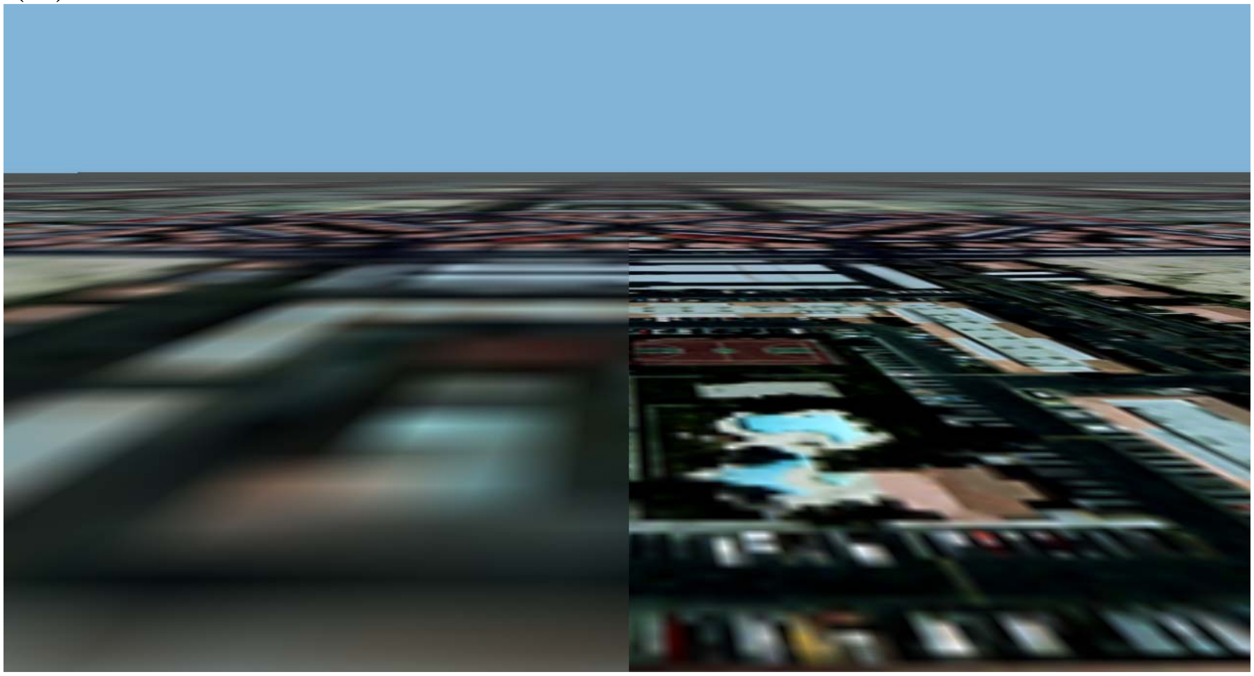


Figure 2. Effects of texture resolution, altitude, and distance on terrain representation. The synthetic environment was created by repeatedly mapping 2 textures of different resolution: 9.6 m on the left and 0.6 m on the right. (The two textures were derived from the same image. For illustrative purposes, the high-resolution texture was "flipped" horizontally before it was mapped.) The simulated altitudes are 300 m and 30 m in Figures 2a and 2b, respectively.

Effects of IG density, altitude, and distance on the number of meters subtended by a pixel are illustrated in Figures 3a and 3b (The two figures represent strips through the lower halves of images depicting 60° vertical fields of view from altitudes of 500 m and 50 m, respectively.). The numbered, horizontal lines mark the image locations at which the designated number of meters (up to 4) would be subtended by individual pixels of IGs with vertical pixel densities of 1024, on the left, and 4096, on the right.

Note that, at a simulated altitude of 500 m (Figure 3a), an IG with a vertical resolution of 1024 could not represent a 1-m texture, even on the nearest terrain, whereas an IG with a vertical resolution of 4096 could represent a 1-m texture on over roughly 35% of the ground area. At a simulated altitude of 50 m (Figure 3b), a texture resolution of 1 m could be represented on about 60% and 80% of the ground plane by IGs with vertical resolutions of 1024 and 4096, respectively.

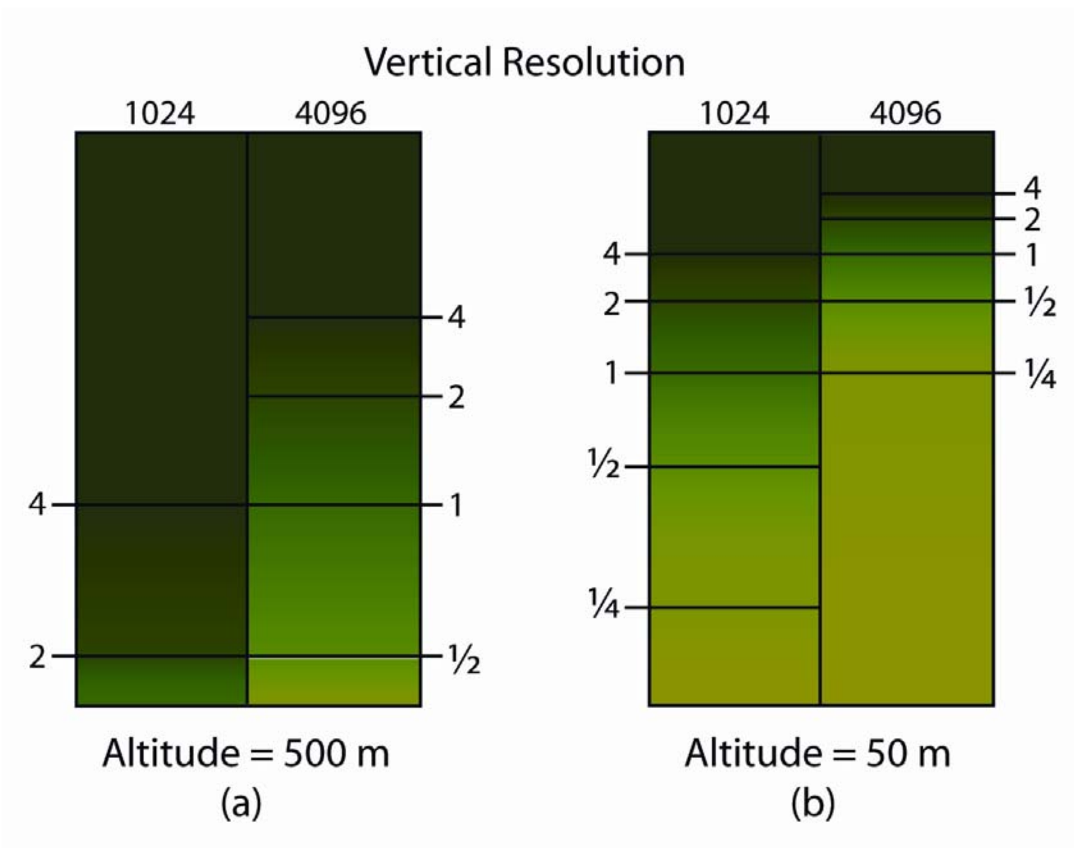


Figure 3. Effects of IG vertical resolution (1024 vs. 4096), altitude (500 m vs. 50 m), and distance on the detail in an image of a flat textured terrain. The numbered, horizontal lines indicate the locations, in the lower half of the image, at which a pixel would subtend the designated numbers of meters (up to 4 m/pixel) if the view plane were perpendicular to the ground surface, the viewing direction were parallel to the view plane normal, and the view plane window subtended ±30° vertically.

Display System

The display system of a flight simulator creates a visible space-time image from a sequence of computer-generated, digital images. Ideally, the display of the spatial image for a given sampled point in time would be an accurate "reconstruction" of the nominal, antialiased image projected onto the view plane internal to the IG. However, for this to be the case, the display system would have to (a) pass, without attenuation, all spatial frequencies up to half the IG's sampling frequency and (b) remove all higher frequencies introduced by the sampling process (Holst, 1998). The nature and extent of deviations from this ideal depend upon the display technology. With most technologies, the high frequencies introduced by sampling are severely attenuated. The higher frequencies in the original antialiased image are also likely to suffer substantial attenuation. Various measures of display resolution (e.g., the highest frequency—in cycles/pixel—that can be produced with a specified modulation) provide information relevant to the amount of attenuation of frequencies up to half the IG's sampling frequency. In general, if the resolution of a display system is low relative to that of the IG, the finer details represented in the digital image may not be visible in the display image. It is important to note, however, that attenuation increases with spatial frequency in *image* units. As we have illustrated, the relationship between image units and environmental units depends upon the simulated viewing distance and angle. Relatively small environmental details in *near* terrain or objects may be well represented, even on a display that severely attenuates the highest frequencies in a digital image.

TEMPORAL CHARACTERISTICS OF COMPUTER-GENERATED IMAGERY

Continuous Space-Time Image

A continuous, time-varying image, internal to an IG, is sampled in time as well as in space. As with any sampled dimension, to prevent temporal aliasing, the temporal sampling rate must be greater than twice the highest temporal frequency in the image.

The Fourier transform of a three-dimensional, space-time image consists of three-dimensional, spatiotemporal-frequency components. The temporal frequency of a given component equals the product of its spatial frequency and its drift speed. Thus, if an IG uses spatial antialiasing filters to limit the maximum spatial frequency in the continuous space-time image, it will indirectly limit the temporal frequencies in that image. Spatial antialiasing filters do *not*, however, ensure that the temporal frequencies are all less than half the temporal sampling rate.

Temporal Aliasing

With current simulator technology, no direct attempt is made to prevent temporal aliasing—that is, the image is not subjected to a temporal, low-pass, presampling filter. Temporal aliasing is therefore possible. If a spatiotemporal-frequency component is temporally aliased, it will have the original spatial frequency but an erroneous, lower temporal frequency and thus an erroneous drift velocity.

Given that the temporal frequencies in a continuous image are a function of its spatial frequencies, the *spatially-antialiased*, continuous images of next-generation, ultra-high resolution systems will typically contain higher temporal frequencies than the corresponding images of current systems. Estimates of the maximum temporal frequencies likely for typical flight scenarios can be used to assess both the extent of temporal aliasing likely with a standard 60-Hz update rate as well as the update rate necessary to eliminate aliasing.

Measures of the temporal-frequency composition of a continuous space-time image could be based on spatial frequencies and velocities (in cycles/degree and degrees/sec or in cycles/pixel and pixels/sec) within spatially-local parts of the image. However, the computations would be complex. It is far simpler to use environmental units (i.e., spatial frequency in cycles/m and flight velocity in m/s). Consider, for example, the space-time image created during constant-altitude, constant-velocity flight over a flat surface textured with a single spatial frequency (e.g., 0.1 cycle/m). Because of the perspective projection, the image of the ground plane will contain a broad band of spatial frequencies. However, every spatial frequency (> 0.0 cycles/pixel) will have the same temporal frequency, as will every point in the image where the luminance varies over time—that is, every point in the image where the projected frequency is passed by the spatial antialiasing filter. This temporal frequency will equal the dot product of the two-dimensional spatial-frequency vector and the two-dimensional velocity vector, in environmental units.

For a given update rate, the simulated ground speed determines the maximum spatial frequency (in the direction of motion) that will *not* be temporally aliased. Figure 4 shows this function for an update rate of 60 Hz. Note that only frequencies higher than about 0.5 cycles/m (maximum texel size = 1 m) will be aliased at a speed of 120 knots, while frequencies as low as about 0.1 cycles/m (maximum texel size = 5 m) will be aliased at speeds greater than 600 knots (see Figure 4). If a specific spatial frequency is aliased at a specific speed, then all higher frequencies will also be aliased at that speed. Given that the spatial-frequency bandwidth of a texture is usually limited by the resolution of the texture and not by the ground pattern it represents, an increase in texture resolution will typically result in aliasing at lower speeds, and, for a given speed, an increase in texture resolution will typically result in an increase in the number of spatial-frequency components that are aliased.

However, building a database with a given texture resolution does not guarantee that that resolution will be present in the spatially-antialiased image: Simulated altitude, distance-along-the-ground, and IG resolution all affect the cutoff frequency of the antialiasing filter (in environmental units) and thus the resolution of the texture that is sampled by the IG. Thus, as illustrated in Figure 5, for a given field of view and texture resolution, the proportion of a flat ground plane in which aliasing could occur is a function of IG resolution and simulated altitude—in addition to ground speed. For a particular altitude, as IG resolution increases, the proportion of the ground plane in which aliasing could occur will increase. Moreover, an increase in IG resolution will result in an increase in the altitude for which some aliasing is likely.

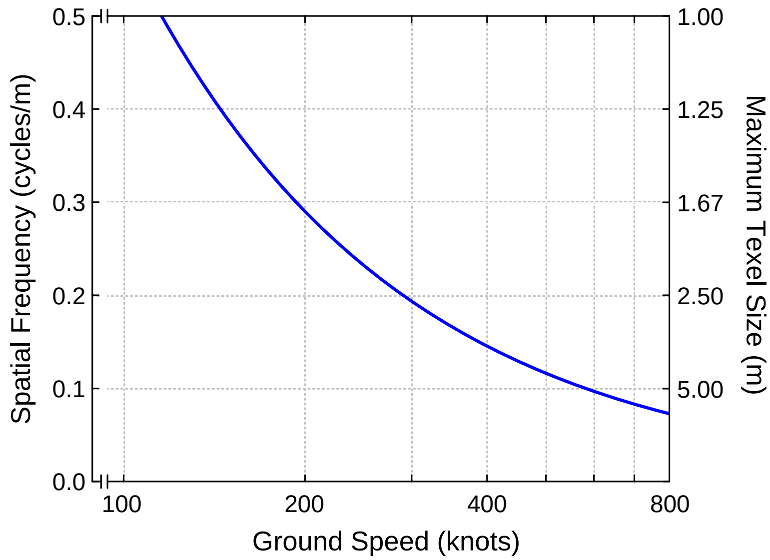


Figure 4. Maximum spatial frequency (in the direction of motion) that will *not* be temporal aliased, as a function of simulated speed (image update rate = 60 Hz). The corresponding maximum pixel size is given on the right axis.

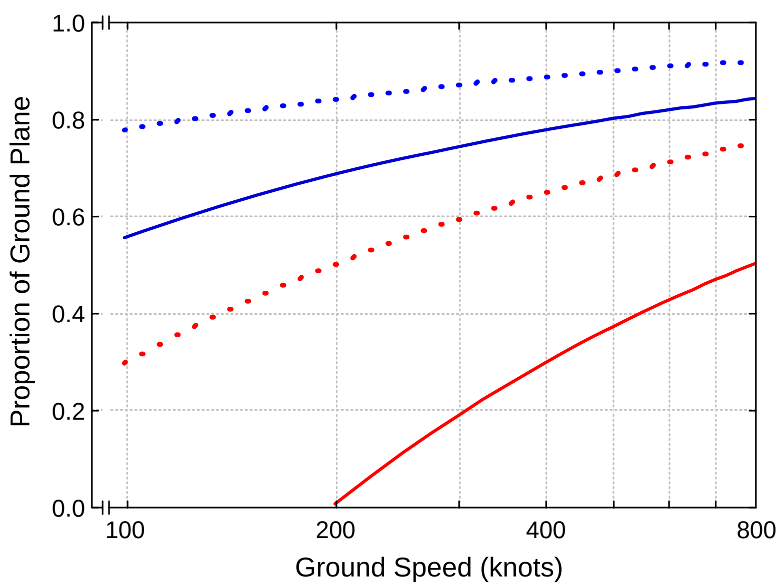


Figure 5. Proportion of an image of a ground plane (subtending the lower half of a 60º vertical field of view) in which some temporal aliasing could occur with a 1-m texture, as a function of simulated speed for altitudes of 500 m (red) and 50 m (blue) and IG vertical resolutions of 1024 (solid) and 4096 (dotted).

Temporal Characteristics of Display Systems

As we noted earlier in this report, the display system of a flight simulator reconstructs a visible space-time image from a sequence of computer-generated, digital images. The fidelity of this reconstruction is affected by the temporal as well as the spatial characteristics of the IG and the display. Ideally, the IG's image-update rate would be high enough to prevent temporal aliasing, and the display system would pass, without attenuation, all spatiotemporal frequency components in the original image, and would remove all sampling-induced components with higher temporal frequencies.

Current flight simulators fail to meet this ideal in a variety of ways. As we have indicated, IG technology does not prevent temporal aliasing. Once temporal aliasing occurs, there is no way for a display system to accurately reconstruct the original, nominal image. However, the band of temporal frequencies passed by a display system, and thus the nature of the distortion, depends upon the display technology. Some display systems pass, with minimal attenuation, temporal frequencies many times greater than half the update rate (e.g., CRTs), whereas others attenuate many temporal frequencies less than half the update rate (e.g., LCDs). If a display system passes temporal frequencies higher than half the update rate, it will pass all the aliased spatiotemporal frequency components. It will probably also pass all of the spatiotemporal frequency components in the original image and many high temporal frequency components introduced by the temporal sampling process. If a display system attenuates temporal frequencies less than half the update rate, it will attenuate the high temporal frequency components introduced by the temporal sampling process, but it is also likely to attenuate some of the spatiotemporal frequencies in the original image. The extent to which it attenuates aliased components will depend upon the temporal frequencies of those components.

Perceptual Effects of Temporal Aliasing

During observation of a display image, an image is formed on the retina of each eye. If the observer's direction of gaze is constant during the observation period, the temporal frequencies in the retinal images will match those in the display image. This correspondence does not hold, however, during movement of the observer's eyes or head. In fact, during certain kinds of eye movements (e.g., smooth pursuit), a temporally aliased component in the display image may not be aliased in the retinal image—and vice versa.

The HVS is sensitive to only a limited band of spatiotemporal frequencies. The maximum spatial frequency falls between 30 and 60 cycles/degree (Wilson, Levi, Maffei, Rovamo, & DeValois, 1990); the maximum temporal frequency falls between 50 and 70 Hz (Watson, 1986). Sensitivity is very low to relatively high spatial frequencies with relatively high temporal frequencies (and to very low spatial frequencies with very low temporal frequencies).

Presumably, any spatiotemporal-frequency component falling within the passband of the HVS may have a perceptual effect. However, the effect of a given component is likely to depend upon other components (both nonaliased and aliased) in the image. The perceptual effects of temporal aliased components within a complex space-time image may thus not be predictable from studies of aliasing within simpler patterns.

As expected, if a single moving spatial sinusoid is temporally aliased, it usually appears to move in accord with its aliased temporal frequency rather than with the temporal frequency in the original image—that is, it appears to move at a lower speed and most often[3] in the wrong direction. If *all* of the spatiotemporal frequencies in a more complex pattern are aliased, the pattern usually appears to move in accord with the erroneous velocity of the *lowest* spatial frequency—as in the well known "wagon wheel effect." Relatively little is known about the perceptual effects of temporally aliased spatiotemporal-frequency components within complex, broadband images that also contain many nonaliased components.

We have used an IG with a resolution of 1280 x 1024 to examine perceptual effects of temporal aliasing during simulated flight over flat terrains textured with complex generic and geospecific patterns. We have found, for most nonrepetitive patterns, that terrain motion appears incoherent in those parts of an image characterized by large numbers of both nonaliased and aliased components. The perceived incoherence increases, at least roughly, with the proportion of aliased components. In our view, the presence of incoherent motion degrades image quality.

Studies of the effects of aliasing on perceived speed during low-level flight have produced inconsistent results. In some experiments, aliasing in the near terrain resulted in an *increase* in the apparent speed of simulated flight; in other experiments, near-terrain aliasing failed to have a significant effect on either apparent speed or glide slope. We suspect that effects of temporal aliasing on velocity perception depend, in part, on the following factors: (a) the proportion of frequencies that are aliased, (b) the proportion of the image that contains aliased frequencies, (c) the spatial frequencies, in cycles/degree, that are aliased, (d) the relative amplitudes of the aliased frequencies, and (e) the eye and head movements of the observer.

Conclusions

The spatial resolutions of the databases and IGs of next-generation flight simulators are expected to be significantly higher than those of current simulators. As a consequence, the nominal, space-time images sampled by the IG may have higher temporal frequencies than those that characterize current systems. If the image-update rate is not greater than twice the highest temporal frequency, temporal aliasing will occur.

Most IGs have an image-update rate of about 60 Hz. While this update rate is adequate to prevent temporal aliasing for current texture and IG resolutions, at most flight speeds and altitudes, temporal aliasing is sometimes present at very low altitudes and high velocities. If a 60-Hz update rate is used with a new ultra-high resolution system, temporal aliasing will occur at higher simulated altitudes and lower simulated speeds. During low-level flight, a large

[3] If perception is consistent with the aliased component, the perceived direction of motion will depend upon the relationship between the temporal sampling rate and the temporal frequency in the original image. For example, if the sampling rate is greater than the temporal frequency but less than two times the temporal frequency, as is often the case, the spatial sinusoid will appear to move in the wrong direction, whereas if the sampling rate is slightly higher than two times the temporal frequency, it will appear to move in the right direction (but at an erroneous speed).

proportion of the image may be characterized by aliasing, and a large proportion of the components within parts of the image may be aliased. If temporal aliasing is extensive, it could seriously degrade perceived image quality and affect a variety of perceptual tasks.

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