Ultra-High-Speed Thermography

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We have all seen high-speed imagery at some point in our lives, be it a video of a missile in flight or a humming bird flapping its wings in slow motion. Both scenarios are made possible by high-speed visible cameras with ultra-short exposure times and triggered strobe lighting to avoid image blur, and usually require high frame rates to ensure the captured video plays back smoothly. Until recently, the ability to capture high-speed dynamic imagery has not been possible with traditional commercial IR cameras. Now, recent advances in IR camera technologies, such as fast camera detector readouts and high performance electronics, allow high-speed imagery.

Challenges prohibiting high-speed IR cameras were based primarily on readout electronic designs, camera pixel clocks, and backend data acquisition systems being too slow. Older readout designs only allowed minimum integration times down to about 10 µs, which in some cases were insufficient to stop motion on a fast moving target without image blur. Similarly, targets with very fast temperature changes could not be sampled at an adequate frame rate to accurately characterize the object of interest. Even with the advent of faster IR cameras, there still remains the hurdle of how to collect high resolution, high-speed data without overwhelming your data collection system and losing frames of data.

Not all challenges for high-speed IR cameras were due to technology limitations. Some were driven by additional requirements that restricted the maximum frame rates allowed. For example, cameras that required analog video output naturally restricted the maximum frame rate due to the NTSC and PAL format requirements of 30 Hz or 25 Hz, respectively. This is true regardless of the pixel rate capabilities of the detector focal plane array (FPA), because the video monitor's pixel rates are set by the NTSC or PAL timing parameters (vertical and horizontal blanking periods).

However, with new improvements in high-end commercial R&D camera technologies, all these challenges have been overcome and we can begin exploring the many benefits of high-speed IR camera technology. The core benefits are the ability to capture fast moving targets without image blur, acquire enough data to properly characterize dynamic energy targets, and increase the dynamic range without compromising the number of frames per second.

Reducing Image Blur with Short Integration Times

With advanced FPA Readout Integrated Circuits (ROIC), IR cameras can have integration times (analogous to exposure time or shutter speed in visible cameras) as short as 500 ns. In addition, new ROIC designs maintain linearity all the way to the bottom of their integration time limits; this was not true for ROICs developed only a few years ago.

The key benefit again is to avoid motion blur as the target moves or vibrates through the field of view of the camera. With sub-microsecond integration times, these new cameras are more than sufficient for fast moving targets such as missiles or in the following example, a bullet in flight.

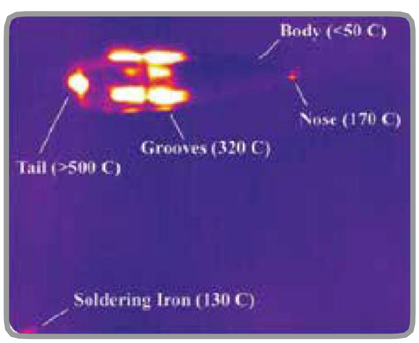
Faster Than a Speeding Bullet

In the following experiment, a high speed IR Camera was used to capture and measure the temperature of a 0.30 caliber rifle bullet in flight. At the point of image capture the bullet was traveling at supersonic speeds (800–900 meters per second) and was heated by friction within the rifle barrel, the propellant charge, and aerodynamic forces on the bullet. Due to this heat load, the IR camera could easily see the bullet even at the very short integration time of 1 µs; so unlike a visible camera, no strobe source is needed.

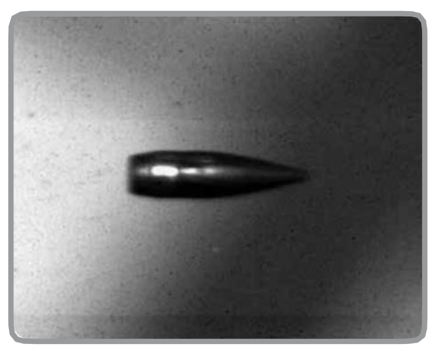
A trigger was needed to start the camera integration time to ensure the bullet was in the Field of View (FOV) of the camera at the time of frame capture. This was done by using an acoustic trigger from the rifle shot, which locates the bullet along the axis of fire to within a distance of several centimeters.

Figure 1a shows a close-up IR image of the bullet traveling at 840 m/s (~1900 mph); yet using the 1 µs integration time, effectively reduced the image blur to about 5 pixels.

Figure 1b shows a reference image of an identical bullet imaged with a visible light camera set to operate with a 2-microsecond integration time. The orientation of the bullets in the two images is identical – they both travel from left to right. The bright glow seen on the waist of the image is a reflection of bright studio lights that were required to properly illuminate the bullet during the exposure. Unlike the thermal image, the visible image required active illumination, since the bullet was not hot enough to glow brightly in the visible region of the spectrum.



Caption:
Figure 1a. Infrared image of a 0.30 caliber bullet in flight with apparent temperature



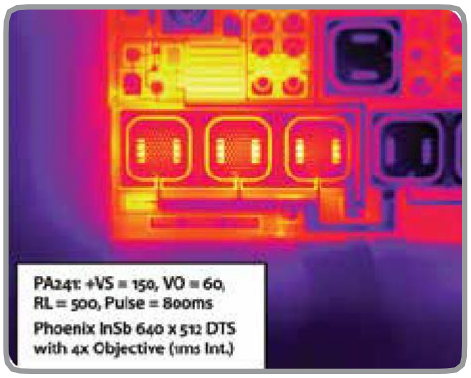
Caption:
Figure 1b. Visible light images of an identical 0.30 caliber bullet in flight

High-Speed Imaging for Fast Transients

Short integration times and high-speed frame rates are not always paired together in IR cameras. Many cameras have fast frame rates but not fast integration times or vice versa. Still, fast frame rates are critical for properly characterizing targets whose temperatures change very quickly.

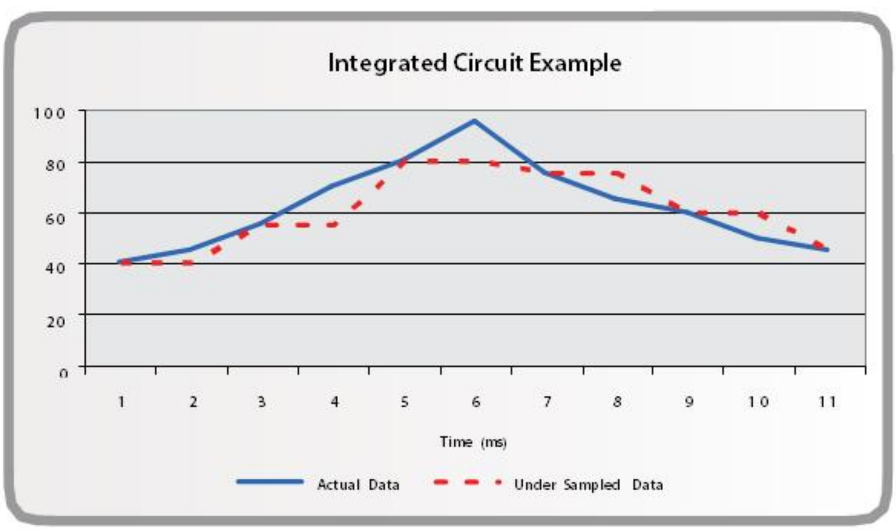
An application where both short integration time and fast frame rate are required is overload testing of integrated circuits (ICs). See Figure 2. The objective of this test is to monitor the maximum heat load the IC experiences when biased and reverse biased with current levels outside the design limits. Without high-speed IR technology, sufficient data might not be captured to characterize the true heat transients on the IC due to under sampling.

This would not only give minimal data to analyze, but could also give incorrect readings of the true maximum temperature.



Caption:
Figure 2. Integrated circuit with 800 ms overcurrent pulse

When the IC was sampled at a frame rate of 1000 Hz, a maximum temperature of 95°C was reported. However, when sampled at only 500 Hz, the true maximum temperature was missed and a false maximum of 80°C was reported (Figure 3).



Caption:
Figure 3. Maximum IC temperature data – actual vs. under-sampled

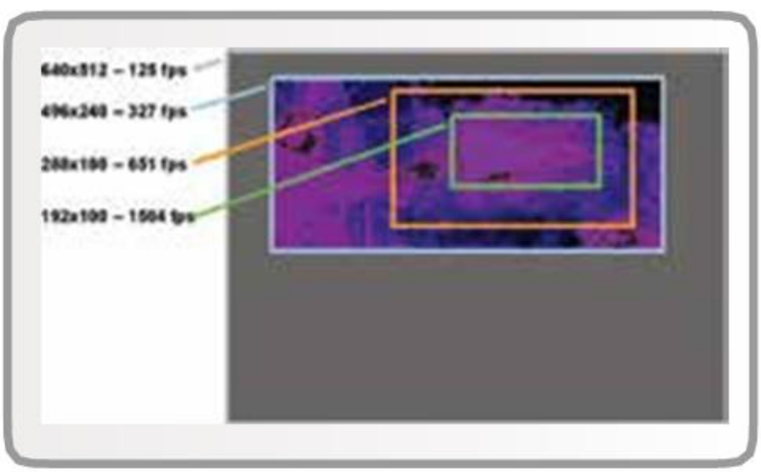
This is just one example of why high-speed IR cameras can be so valuable for even simple applications that don't necessarily appear to benefit from high speed at first consideration.

Pixel Clock vs. Analog to Digital Taps

High-speed IR cameras require as a prerequisite a combination of a fast pixel clock and a higher number of analog to digital (A/D) converters, commonly called channels or taps. As a frame of reference, most low performance cameras have two channels or A/D converters and run at lower than 40 megapixels/second clock rates. This may sound fast, but when you consider the amount of data, that translates into around 60 Hz in most cases.

High-speed IR cameras on the other hand typically have a minimum of four channels and have clock speeds of at least 50 megapixels/second. In turn they offer 14-bit digital data at frame rates of over 120 Hz at 640 × 512 window sizes. In order to increase frame rates further, IR cameras usually allow the user to reduce the window size or number of pixels read out from FPA. Since there is less data per frame to digitize and transfer, the overall frame rate increases.

Figure 4 illustrates the increase in frame rates relative to user defined window sizes.



Caption:

Figure 4. Example of FPA window sizes relative to frame rates

Newer camera designs offer 16 channels and pixel clocks upwards of 205 megapixels/second. This allows for very fast frame rates without sacrificing the window size and overall resolution.

Preset Sequencing Increases Dynamic Range

High-speed IR cameras have an additional benefit that does not relate to high- speed targets, but rather to increasing the dynamic range of the camera. By coupling a high-speed IR camera with a data capture method known as superframing, you can effectively increase the camera's dynamic range from 14 bits to around 18–22 bits per frame.

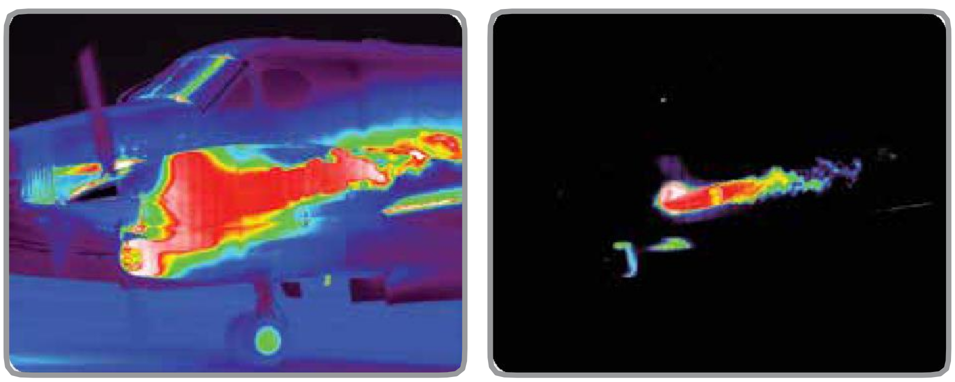
Superframing involves cycling the IR camera through up to four multiple integration times (presets), capturing one frame at each preset. This results in multiple unique data movie files, one for each preset.

This data is then combined by using off-the-shelf ABATER software. The software selects the best resolved pixel from each unique frame to build a resultant frame composed of data from all the collected data movie files at varying integration times.

This method is especially beneficial for those imaging scenes with both hot and cold objects in the same field of view.

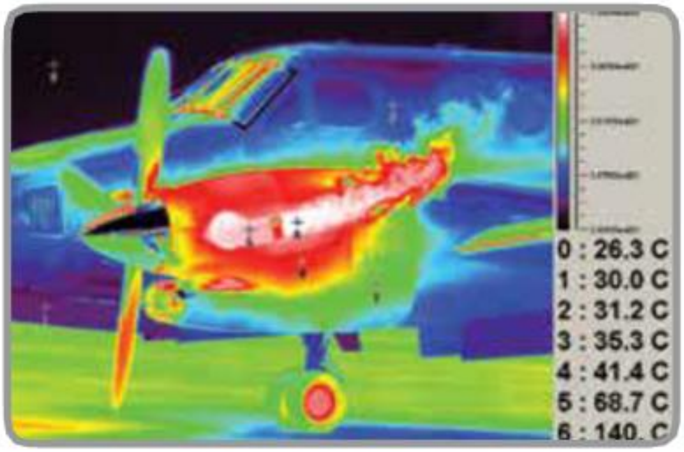
Typically a 14-bit camera cannot image simultaneously both hot and cold objects with a single integration time. This would result in either over exposure on the hot object or under exposure on the cold object.

The results of superframing are illustrated in the Beechcraft King Air aircraft images in Figure 5, captured at two different integration times. While the aircraft can be clearly seen in the left image (Preset 0 = 2 ms integration time), there are portions of the engine that are clearly over exposed. Conversely, the right image in Figure 5 (Preset 1 = 30 µs integration time), shows engine intake and exhaust detail with the remainder of the aircraft underexposed.



Caption:
Figure 5. Active aircraft engine imaged at integration rates of 2 ms (left) and 30 µs (right)

When the two images in Figure 5 are processed in ABATER software, the best resolved pixels are selected and used to build a single resultant superframed image with no over or under exposed pixels (Figure 6).



Caption:
Figure 6. Superframed image created with ABATER software from Preset 0 and Preset 1 data

As you may have figured out, the down side to this method of data collection and analysis is the reduction in the frame rate by the number of Presets cycled. By applying some simple calculations a 100 Hz camera with two Presets will provide an overall frame rate of 50 Hz, well under the limits of our discussion of high speed IR imagery. This only reinforces the need for a high speed camera. If a 305 Hz camera is superframed as in the example above, a rate of over 150 Hz per preset frame rate is achieved. This rate is well within the bounds of high speed IR imaging.

Conclusions

Sophisticated IR cameras are now available with advanced readout electronics and high speed pixel clocks, which open the door for high speed IR imagery. This allows us to expand the boundaries of which applications can be solved using IR camera solutions. Furthermore, it allows us to begin capturing more data and increase our accuracy for demanding applications with fast moving targets, quick temperature transients, and wide dynamic range scenes.

With the release of this new technology in the commercial IR marketplace, we can now begin to realize the benefits of high-speed data capture, once only available to the visible camera realm.

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