Superframing: Scene Dynamic Range Extension of Infrared Cameras

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ABSTRACT

Infrared cameras are often used to capture high-speed digital video of scenes with enormous ranges in in-band brightness. A simple example of this would be a man standing next to a hot fire. Under normal operating conditions, it can be next to impossible to fully span a scene like this with the brightness dynamic range of an infrared camera. The brightest or hottest parts of the image will often be saturated, while at the same time the darkest or coldest parts of the scene may be buried in the noise floor of the camera and appear black in the image. Varying the exposure by changing the integration time is necessary to maximize the useful information recorded by the camera, but sometimes a single integration time is not enough to fully encompass a scene's variations. The technique of superframing consists of varying the integration time of the camera from frame to frame in a cyclic manner, then combining the resulting subframes into single superframes with greatly extended dynamic ranges. The technique and some sample data are described in this paper.

Keywords: superframe, superframing, high-speed, high frame rate, midwave infrared, InSb, infrared camera, dynamic range extension, RTools, radiometry, radiometric software

1. INTRODUCTION

Superframing is a technique by which the effective scene brightness dynamic range of an infrared imaging system can be extended dramatically while maintaining thermal contrast, even at low temperatures. A superframe is an image created by reducing a dataset consisting of multiple images of a scene taken in rapid succession, typically in cycles of four images called subframes. Each subframe has a different exposure, usually controlled by changing the shutter speed or integration time of the imaging system. The imaging system acquires a number of cycles of subframes, and the post-processing procedure reduces each cycle to a single superframe. The superframes are then played in a sequence at a rate which is N times slower than the imaging system's inherent frame rate, where N is the number of subframes in a cycle, usually four. Thus, a 100 frames/second imaging system with subframe cycling collapses down into a 25 frames/second superframe image sequence.

The superframing technique is particularly useful for infrared camera systems that are used to image scenes with enormous differences in temperature, such as a rocket launch or explosion. In a launch, the hardbody of the rocket can be very cold, particularly if it is of the liquid-fueled type. An infrared camera will have to be set to high sensitivity to properly image the thermal features on the cold hardbody surface. But right after ignition, the bright exhaust plume will rapidly saturate the camera that is set to image the hardbody. This problem can be solved by rapidly reducing the sensitivity of the camera, usually by reducing the integration time from several milliseconds for an indium antimonide (InSb) camera with a 3 to 5 micron bandpass to 10 microseconds, for example. However, one then finds that the hardbody vanishes from the image, since it does not have enough IR brightness to get above the noise floor of the now reduced-sensitivity camera. Rather than train multiple IR cameras set to various different integration times on the rocket, it is easier and much more cost-effective to command a single camera system to cycle through multiple exposures and acquire a set of subframe cycles, then collapse that set of subframes into a single superframe sequence. This will also eliminate the parallax errors that are inherent in any camera system with co-axial multiple imagers.

Many scenes with large brightness dynamic ranges are also temporally dynamic. A rapidly changing scene can result in apparent movement within the scene during individual subframe cycle. When the superframing algorithm is applied, there will be some artifacts in the resulting superframe caused by misregistration from one subframe to the next. A very high frame rate camera mitigates this problem, and for the data shown in this paper, a fast camera system capable of acquiring 100 frames per second was used. The images were at a frame size of 640 by 512 pixels, enabling fine detail to be captured. Future camera systems equipped with focal-plane arrays with 16 or more outputs will further reduce the registration problem.

The superframe generating algorithm can be quite simple. If a pixel in the first subframe is saturated, the algorithm selects the corresponding pixel from the next subframe that has a reduced exposure. If that pixel is satisfactory, the algorithm stops. If not, it checks the corresponding pixel in the next subframe for suitability, and so on. Since all the pixel values in each subframe have been converted to engineering units, the resulting image has smooth transitions from pixel to pixel, even though those two adjacent pixels may have come from two different subframes with quite different digital count values. The algorithm can get more complicated if one attempts to co-register the subframes in a particular cycle to account for a target moving within the cycle. The registration may be necessary if the target is moving rapidly across the field of view. This alignment can be done by using fiducial points on the target or within the scene and translating, rotating or warping the subframes to align the fiducial points on all subframes within a cycle. If the target is a rocket or an aircraft, a properly aligned tracking gimbal can mitigate any image translation errors by keeping the target centered in the camera's field of view.

2. RADIOMETRIC CALIBRATION

In order to compare pixels across different subframes and generate a radiometric image, the camera must be calibrated by using standards of known in-band radiance. This is done by using laboratory blackbodies that are designed to have emissivities of very nearly unity and precise temperature control. When the blackbody is set to a temperature of 100 C, for example, one can integrate a 100 C Planck curve over the desired waveband and multiply by the in-band emissivity and the camera's normalized spectral response to compute the in-band radiance of the source, expressed in Watts/(cm^2-sr). One finds that the camera's response to a source is quite linear in radiance, as shown in Figure 1 below. This is a plot of the digital count values in a region of interest centered on the calibration source as a function of source radiance. A simple blackbody calculator is used to convert source temperatures into radiance values. The camera used for this experiment is an Indigo Phoenix InSb RDAS system. The RDAS consists of a four-output 640 by 512 pixel focal-plane array in a closed-cycle package with two Cypress Hotlinks streaming serial image data to a host PC, which absorbs the image data using ThermaCAM® RTools either to RAM or directly to a hard drive. This particular camera has a 3 to 5 micron cold filter in it, a standard bandpass for imaging through the atmosphere in the midwave IR band. The calibration source is a Santa Barbara Infrared cavity blackbody that can be controlled from 50 C to 1000 C, and a Mikron 340E blackbody that can range from -20 C to 150 C. The temperature span shown in Figure 1 is 30 to 150 C. Beyond 150 C, the camera becomes saturated for this particular integration time.

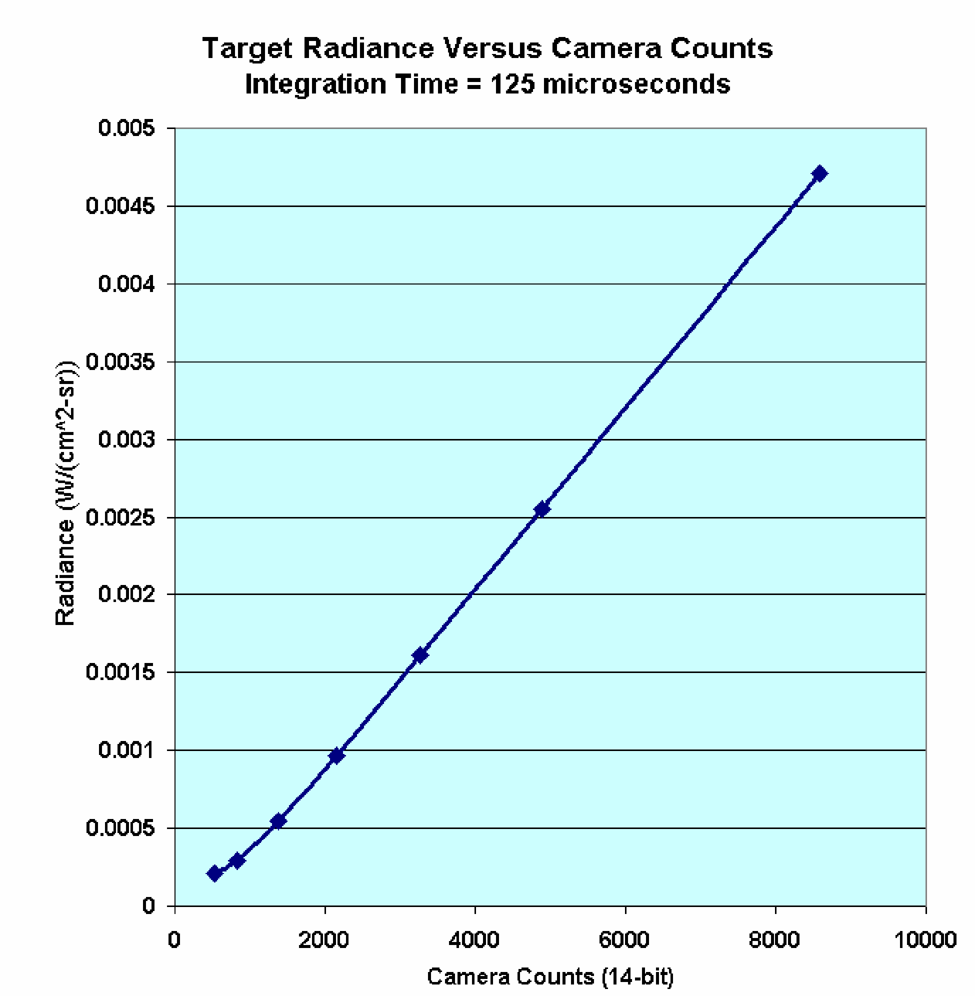


Figure 1. Camera counts versus target radiance for a 125 microsecond integration time.

The camera signal, measured in 14-bit counts, is very linear over a subset of the data. Values above and below this range of radiance are discarded in the calibration. If one chooses the integration times carefully, the radiance ranges for each subframe will overlap, making it possible to choose a particular pixel's radiance value from a linear region of a particular subframe's calibration curve. Figure 2 shows typical calibration curves for four subframes chosen to overlap to give complete coverage over the specified radiance range, which corresponds to calibration source temperatures from 0 C to about 200 C. Another advantage to superframing is that thermal contrast is enhanced over a wide range of scene temperatures. Note the 2000 microsecond curve in Figure 2. It has a slope that is quite small compared to the other three curves. The responsivity in the image (defined as the change in counts for a change in scene temperature) is equal to the inverse of this slope, and thus is quite high, yielding large thermal contrasts in portions of the image where temperatures are near ambient. At the same time, the scene temperature dynamic range is still preserved by the existence of the short integration time subframes that can handle much higher scene temperatures.

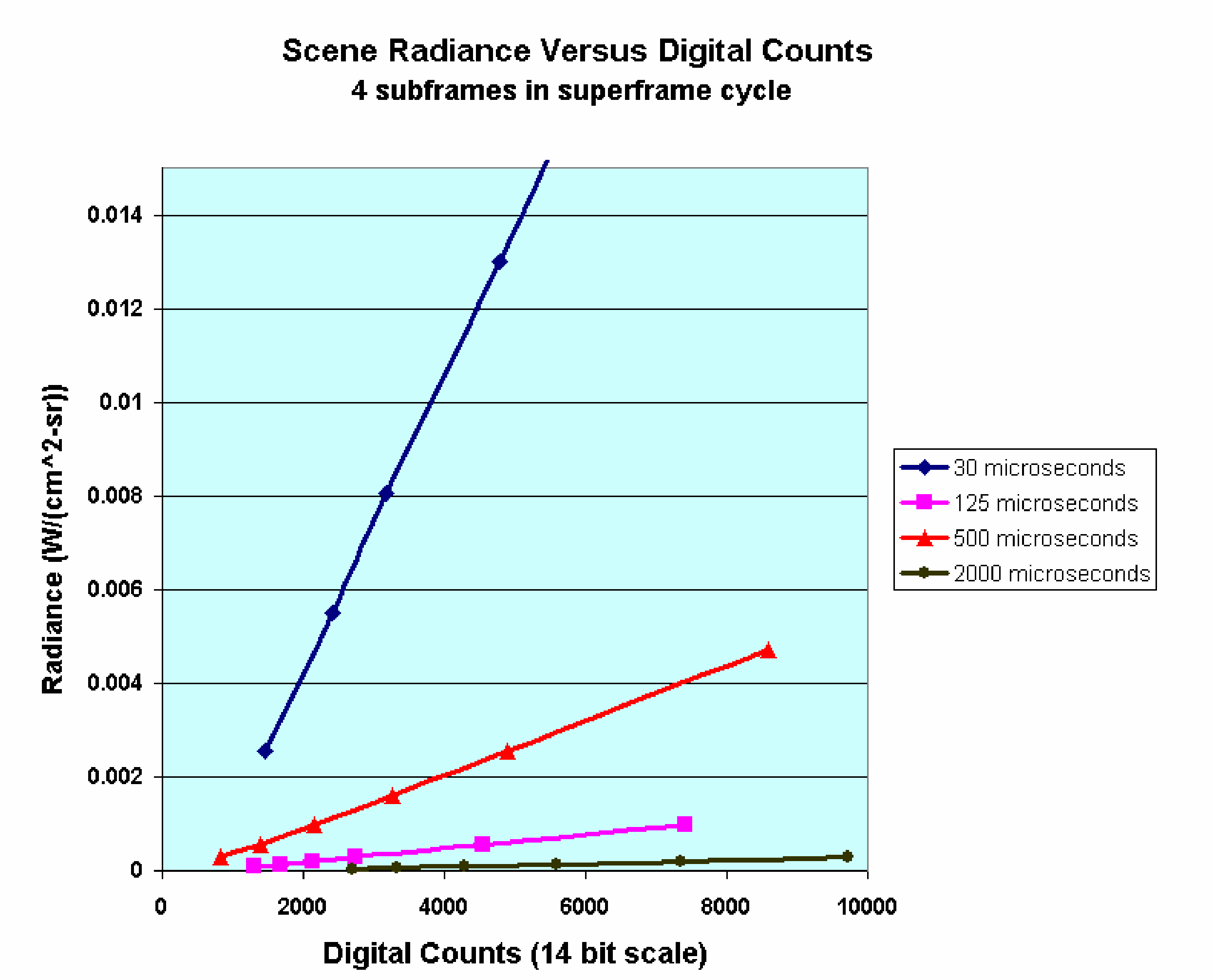
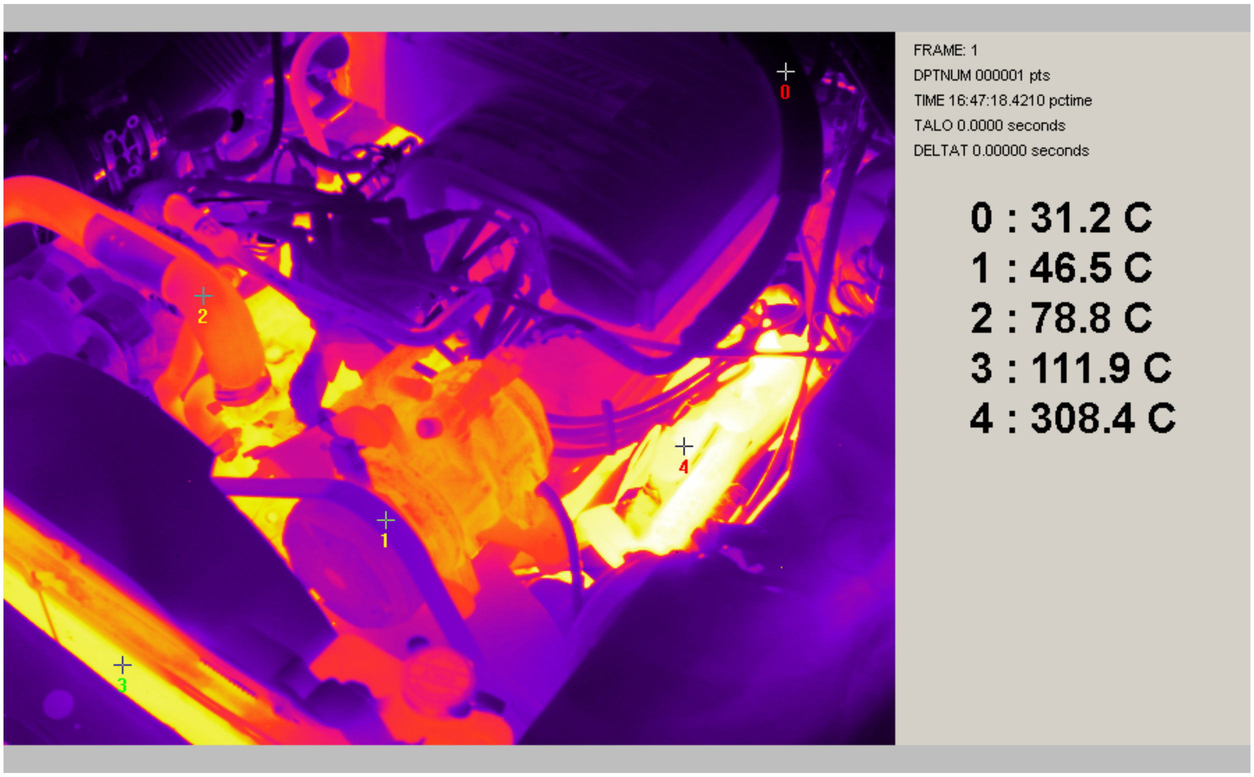


Figure 2. Radiance versus count curves for 4 subframes, each with different integration times, within a superframe.

3. SUPERFRAME EXAMPLES

One common infrared scene that contains a large range of IR radiance values is an automobile engine compartment. The exhaust manifolds can reach temperatures of 600 C and above, while rubber hoses carrying cold refrigerant to the air conditioning system can be below ambient temperature, an observation supported by the presence of water condensation on these hoses on a humid day. An image of the engine compartment of a Ford Mustang at idle was taken, as shown in Figures 3, using a superframing camera system with 4 subframes with integration times of 2000 microseconds, 500 microseconds, 125 microseconds and 30 microseconds respectively. The choice of these integration times was made on the basis of a logarithmic series – each subframe after the first has an integration time (and hence exposure) that is 4 times smaller than the preceding integration time. The effective radiance dynamic range of the system is improved by about a factor of 200, an enormous gain. Radiance dynamic range is defined here as the ratio of the highest radiance measurable to the lowest radiance measureable, where both values are within the linear portion of the camera's response curve, as shown in Figure 1. The software used to acquire and process this imagery is Indigo Systems' RTools software suite, a radiometric acquisition and analysis package.



```
FRAME: 1
DPTNUM 000001 pts
TIME 16:47:18.4210 pctime
TALO 0.0000 seconds
DELTAT 0.00000 seconds

0 : 31.2 C
1 : 46.5 C
2 : 78.8 C
3 : 111.9 C
4 : 308.4 C
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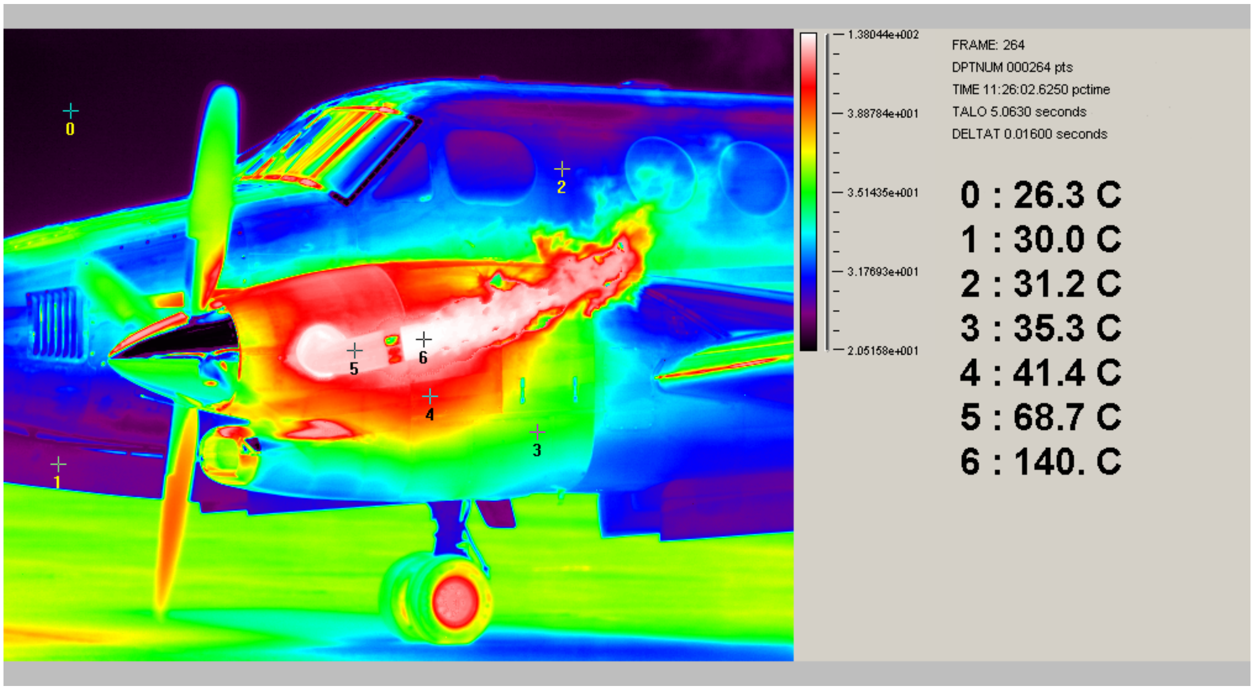
Figure 3. A superframe image of a Mustang engine idling.

Figure 3 has a temperature dynamic range of about 300 C, with excellent preservation of thermal contrast over the entire range of scene temperatures. The light signal was attenuated through a neutral density filter that has a transmission of 10%, in order to achieve linearity over such a large temperature range. There is no single integration time for an InSb camera that could reproduce these images as they are shown here. A 2000 microsecond integration time image will have large saturated areas around the hot exhaust pipe, and a 30 microsecond time will have large dark areas in the image because the light signal collected by those pixels is below the noise floor of the focal-plane array. Only the combination of a neutral density filter to reduce the apparent radiance by a factor of 10 combined with superframing produces a high-contrast image like this.

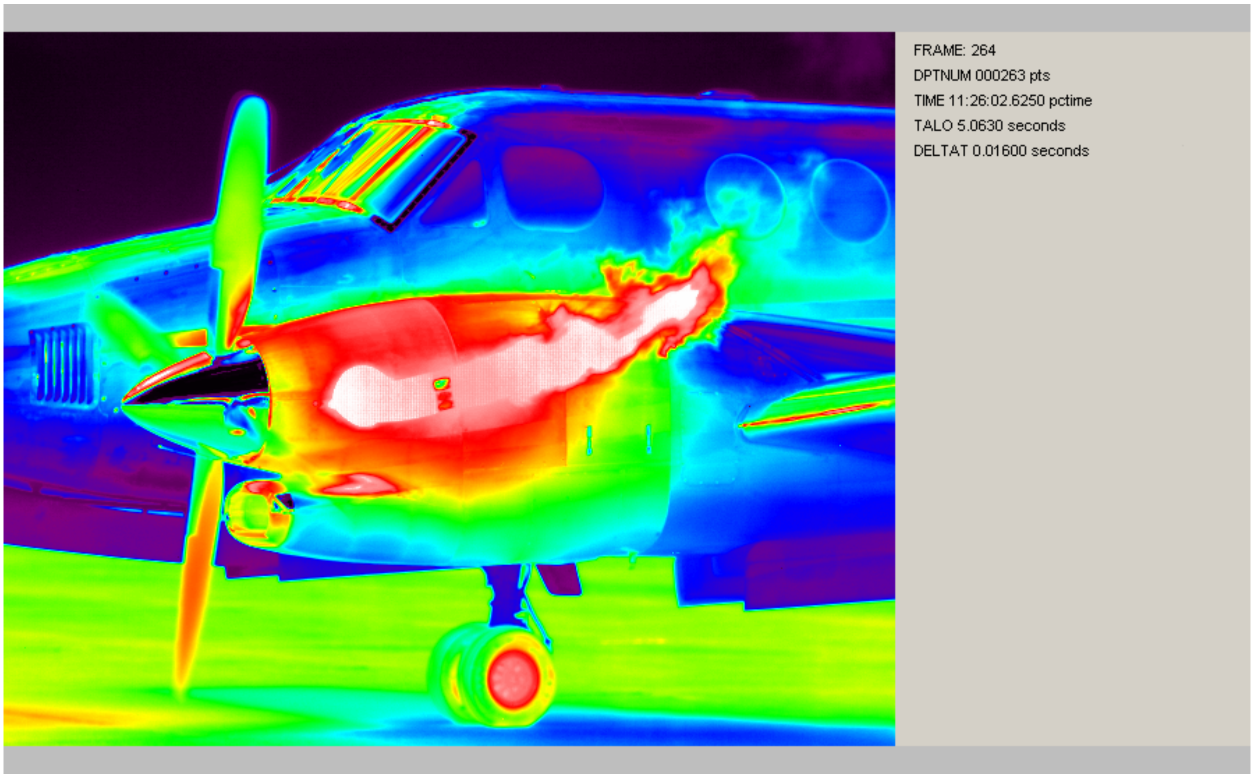
Another interesting example of a superframe image is shown in Figure 4, which is of a Beechcraft King Air turboprop engine. Most of the temperatures indicated by the crosshairs are below 50 C, since that is the dominant scene temperature in the image, but effective temperature measurements much higher than one can achieve with a single integration time are also indicated. These effective temperatures assume that the target has an emissivity of unity, which is probably not correct for the exhaust plume itself. Figure 5 shows the 2000 microsecond subframe that corresponds to the superframe shown in Figure 4. The exhaust plume is in complete saturation over a rather large region of the image. The radiometric data in the saturated region of Figure 5 are lost, whereas the radiometric data from all pixels in the superframe image shown in Figure 4 are preserved.



FRAME: 264
DPTNUM 000264 pts
TIME 11:26:02.6250 pctime
TALO 5.0630 seconds
DELTAT 0.01600 seconds

0 : 26.3 C
1 : 30.0 C
2 : 31.2 C
3 : 35.3 C
4 : 41.4 C
5 : 68.7 C
6 : 140. C

Figure 4. A superframe image of a Beechcraft King Air with idling engine with indicated temperatures of numbered regions of interest.



FRAME: 264
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TIME 11:26:02.6250 pctime
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DELTAT 0.01600 seconds

Figure 5. The 2000 microsecond integration time subframe image used to create the superframe in Figure 4. Note the saturated exhaust plume.

4. SUMMARY

Superframing is an increasingly popular method of increasing the dynamic range of infrared cameras. The enabling technology is two-fold. One is the availability of commercial high-speed focal-plane arrays with multiple outputs so that different sectors of the readout can be streamed out to multiple digitizers simultaneously, making the camera run at frame rates of hundreds of frames per second. The other is the low-cost of high-performance PCs that can absorb high data rates from the camera, as well as rapidly post-processing the data into superframes. Applications for superframing include diagnostics of a diverse range of engines, including internal combustion, gas turbine and jet engines, or any process that involves both high and low surface temperatures in a scene. The technique can also be applied to condition monitoring of liquid fuel rockets during launch, and surveillance applications where the subjects of surveillance are obscured by ground fires or other thermal camouflage.