

Thermal Resolution Specification in Infrared Scene Projectors

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ABSTRACT

Infrared scene projectors (IRSPs) are a key part of performing dynamic testing of infrared (IR) imaging systems. Two important properties of an IRSP system are apparent temperature and thermal resolution. Infrared scene projector technology continues to progress, with several systems capable of producing high apparent temperatures currently available or under development. These systems use different emitter pixel technologies, including resistive arrays, digital micro-mirror devices (DMDs), liquid crystals and LEDs to produce dynamic infrared scenes. A common theme amongst these systems is the specification of the bit depth of the read-in integrated circuit (RIIC) or projector engine, as opposed to specifying the desired thermal resolution as a function of radiance (or apparent temperature). For IRSPs, producing an accurate simulation of a realistic scene or scenario may require simulating radiance values that range over multiple orders of magnitude. Under these conditions, the necessary resolution or “step size” at low temperature values may be much smaller than what is acceptable at very high temperature values. A single bit depth value specified at the RIIC, especially when combined with variable transfer functions between commanded input and radiance output, may not offer the best representation of a customer’s desired radiance resolution. In this paper, we discuss some of the various factors that affect thermal resolution of a scene projector system, and propose some specification guidelines regarding thermal resolution to help better define the real needs of an IR scene projector system.

Keywords: Infrared Scene projection, IRSP, hardware-in-the-loop, HWIL, MIRAGE, thermal resolution

1. INTRODUCTION

Infrared scene projectors (IRSPs) are primarily used to produce dynamic scenes for testing infrared imaging systems and associated signal processing algorithms. In many IRSP applications, it is desirable to produce infrared scenes that approximate reality as closely as possible, with the ideal being to produce a scene which the sensor under test cannot differentiate from reality. To approach this ideal, IRSPs must be capable of producing a wide range of radiance levels, with a fidelity comparable to that of the sensor under test. Current IR sensors can distinguish apparent temperature differences of less than 10 mK. Realistic scenarios may include scenes with complex content near ambient temperatures, while also including one or more very hot objects (burning vehicles, engine exhaust, etc.). Producing a system that is able to simultaneously present a very hot object within a complex, cooler environment is one of the key challenges in modern IRSP design.

The apparent temperature of an object is defined as the temperature of a blackbody that produces the equivalent integrated radiance over the spectral band of interest. The well-known Planck Function (shown below) describes the radiance of a blackbody as a function of both wavelength and temperature. Figure 1 shows the radiance (L) from a source integrated over the mid-wave (MWIR), or 3.0-5.0 μm band for temperatures (T) 200K to 2000K. The radiance is plotted using a logarithmic scale in order to emphasize that this temperature range covers almost 7 orders of magnitude in radiance.

$$L(\lambda, T) = \frac{2hc^2}{\lambda^5 (e^{hc/\lambda kT} - 1)} d\lambda$$

Merely producing radiance over a wide range is not sufficient for generating a high-fidelity scene. The radiance values must be generated with sufficient resolution to accurately depict any real contrast throughout the scene. For example, a nighttime scene may span only a few degrees in apparent temperature, and thus require a thermal resolution of 0.1C or less to accurately reproduce. Representing a very hot target (over 500K, for example) may not require such fine thermal resolution, however. The addition of the nonlinear variation of radiance with temperature can further complicate the specification of thermal (radiance) resolution.

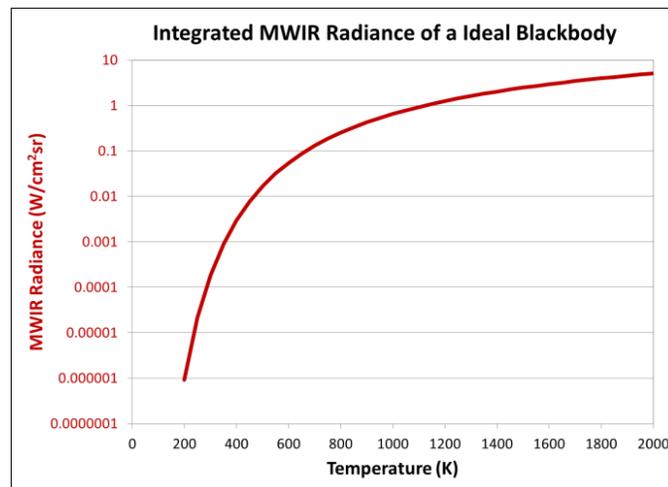


Figure 1. Integrated MWIR radiance as a function of temperature from 200-2000K. The radiance covers almost 7 orders of magnitude. from 200-2000K.

IRSPs are rarely procured as an end-to-end system from a single provider. Various providers typically specialize in one area or another, such as emitter array technology, emitter drive electronics, system control electronics, or scene generation. As a result, such systems are often specified, developed and procured in a ‘piece-meal’ manner. This can unfortunately lead to subsystems that cannot support desired system requirements when interfaced with other subsystems. A key goal of this paper is to describe some of the pitfalls that can arise when specifying IRSP systems, and to provide some suggestions for properly defining thermal resolution requirements to enhance the likelihood of realizing the desired end-system performance.

2. SCENE PROJECTORS AND THERMAL RESOLUTION

As mentioned above, IRSPs are generally comprised of several subsystems. The minimum incremental step in radiance of an integrated IRSP system at a given output radiance is limited by the step sizes of its subsystems at that radiance. Each of these subsystems must be considered when determining system resolution. Figure 2 shows a block diagram of a typical IRSP system. A scene generator system outputs a digital data stream representation of the desired scene, which may consist of actual digitally-recorded IR scenes, synthetically-generated scenes and/or targets, or a combination of both. This scene data is then typically transferred to a set of electronics for digital preprocessing. These preprocessing electronics may format and perform some transformations to the data before transmission to the emitter array and its associated drive electronics. Each individual subsystem has its own ‘native’ response to a

commanded input value, and therefore its own effect on the resulting output radiance and thermal resolution. Each of these subsystems is addressed individually in later sections of this paper, with a focus on their impact on overall thermal resolution and the protocol used to transfer data to the subsequent subsystem.

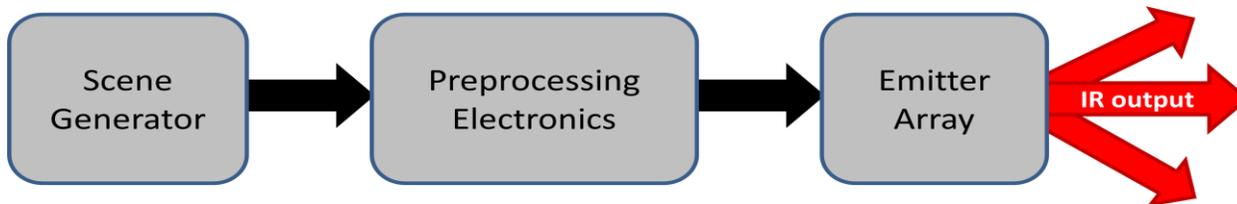


Figure 2. Block diagram of a typical IRSP system.

As mentioned previously, despite their convenience, single-value resolution requirements are not well-suited for systems with dynamic ranges that cover multiple orders of magnitude, and this is also true for their component subsystems. For example, consider a typical terrestrial scene with an apparent background temperature of 300K and a required thermal resolution of 0.1K. Note that an IRSP system meeting these requirements would be capable of producing a reasonable IR simulation of a typical ambient scene, however it would not be capable of exercising a typical modern MWIR imager (with NETD ~ 15 mK) to its sensitivity limits. An apparent temperature of 300K is equivalent to a MWIR radiance of 1.87×10^{-4} W/cm²-sr. Similarly, a 0.1K step at 300K is equivalent to a radiance step of 6.8×10^{-7} W/cm²-sr, or about a 0.4% change in absolute radiance. In order to accommodate a 1500K object within the scene (MWIR radiance of 2.47 W/cm²-sr, with the above constant step size, the total system dynamic range would require more than 3.5 million steps (i.e. greater than 21 bits). At 1500K, this constant step size would equate to an apparent temperature change of less than 0.0002K, which is far smaller than necessary at that high temperature. While achieving that example thermal resolution across such a wide IRSP dynamic range may be relatively straightforward for some subsystems, such as the scene generator, achieving the corresponding resolution in other parts of the system, such as the emitter array, may be impractical or impossible.

Despite the above, many IRSP requirements do specify resolution in terms of a single value for resolution, simply providing a required number of bits with no indication of what the desired step size is at any radiance value. In the following sections, the inherent difficulties with the single-value resolution approach will be addressed in more detail, and the benefits of alternate methods for specifying thermal resolution requirements for different subsystems will be explored.

2.1 Emitter Arrays

The emitter array is the core of an IRSP and places an absolute limit on the radiance output and radiance resolution of the system. Many types of emitter arrays are currently in use or in development, including resistive arrays, DMDs, LED arrays and liquid crystal based projectors. Each technology presents its own benefits and limitations to the user. The purpose of this discussion is not to suggest that any one technology is 'better' than another, but rather to delineate some of their differences and described how those differences affect the thermal resolution of the overall system. Each end-user will need to weigh the advantages and disadvantages when deciding which technology to utilize for a particular type of test. Three emitter types will be discussed in more detail: resistive arrays, DMD arrays and LED arrays.

2.1.1 Resistive arrays

Resistive arrays are one of the more ubiquitous technologies used in IRSPs [1,2]. Such systems control the current flowing through individual resistor pixel elements to heat them to a desired temperature in order to generate an infrared scene. Digital micro-mirror devices (DMDs) are another common technology used in infrared scene projection [3]. These devices have an array of small mirrors which can be switched between two positions in order to reflect or not reflect radiance from a source. Intermediate temperatures are generated by rapid modulation of the individual mirror positions. A third technology, currently in development, is the use of an array of IR light emitting diodes (IRLED) [4,5]. These are similar to resistive arrays in that the current to individual pixels is controlled to produce the desired apparent temperature, but the radiation is produced by an LED rather than via blackbody radiation due to heating of an emissive structure.

Resistive arrays are the most common type of IR emitter technologies currently in use. Resistive arrays use a read-in integrated circuit (RIIC) to control the current flowing through each of the resistor pixel elements. Current state-of-the-art resistive arrays can achieve apparent temperatures up to 700K in the MWIR (3-5 μm) band [1]. New resistive technologies using high-temperature materials and high-power RIICs are currently under development with the goal of achieving temperatures in excess of 1500K [2,6]. Resistive array RIICs typically have a near-linear current response to their input drive,(in counts for a digital system or voltage for an analog system). The digital RIICs currently in use have 16-bit inputs, with approximately 14-bit precision in selecting pixel current. Analog RIICs currently in use have similar limits on their precision due to the high speed digital-to-analog converters used in their drive electronics.

To better illustrate the thermal resolution of a resistive array, consider that the power (P) dissipated in an idealized resistor is given by the well-known equation: $P = I^2R$, where I is the current flowing through the emitter and R is the resistance of the emitter. At relatively low temperatures (typically <600K) the physical temperature (T) of the emitter pixel is primarily determined by the conductance (κ) of its supporting 'legs' given by: $T - T_{sub} = \frac{P}{\kappa} \propto I^2$, where T_{sub} is the temperature of the array substrate. Note that in real pixels, this simplified relationship changes as losses due to radiance grow at higher temperatures, and the emitted radiance is also lowered due to non-unity fill factor and non-unity emissivity. The apparent temperature of an idealized resistive array as a function of drive current is depicted by the blue curve in Figure 3a below.

The radiance output of the above idealized resistive emitter pixel is described by the Planck equation, which leads to a highly non-linear radiance response as a function of RIIC current. This behavior turns out to be fortuitous when considering the relative thermal (radiance) resolution at any given point. Figure 3a shows the radiance vs. current (red) and apparent temperature vs. current (blue) for an idealized resistive array with 14-bit precision in RIIC current and capable of producing an equivalent radiance of 1500K in the MWIR. Note that the radiance curve is plotted on an exponential scale. In Figure 3b, the corresponding radiance resolution and thermal resolution of this idealized resistive array are depicted as functions of apparent temperature. As shown, resistive arrays inherently have smaller radiance step sizes at low radiance and larger step sizes at higher radiance levels, which is the most desirable resolution behavior. It should be noted that a real system would require more current at higher apparent temperatures in order to overcome radiance losses.. Including these radiance losses would lead to slightly larger steps at lower radiance levels and smaller steps at high radiance levels, but the overall trend would be similar to the idealized version presented here.

Figure 4 shows the measured thermal resolution of an actual SBIR MIRAGE resistive array as a function of apparent temperature. For resistive arrays, specifying a simple 14-bit precision on the RIIC current happened to produce a system that had a desirable, variable thermal step size. However, as will be discussed in later sections, even though the emitter array may be capable of providing a given thermal resolution, the other parts of the system may significantly degrade the thermal resolution (i.e. increase the thermal step size).

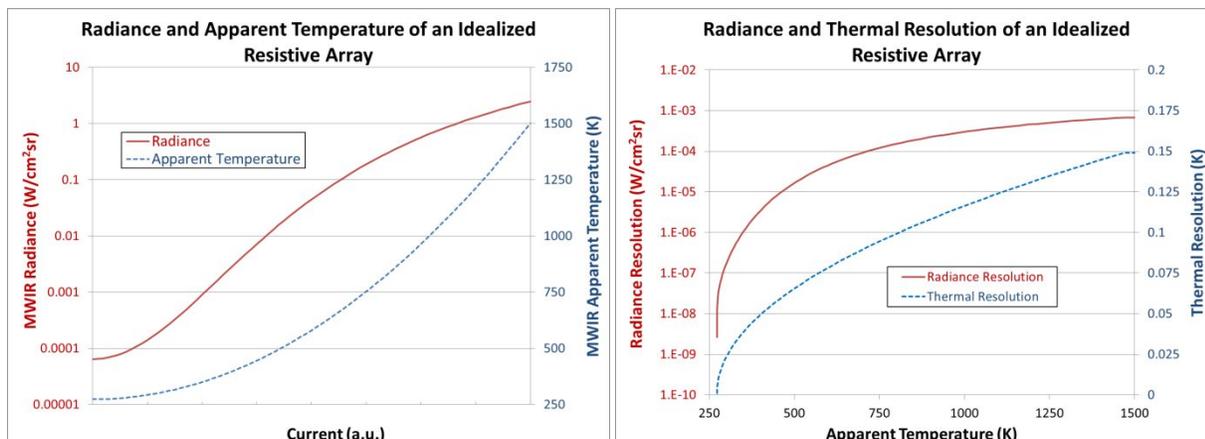


Figure 3. Radiance, apparent temperature and resolution of an idealized resistive array. The plot on the left (3a) shows the relationship between current, radiance and apparent temperature for an idealized resistive array. The plot on the right (3b) depicts the radiance and thermal resolutions for the same idealized pixel as a function of apparent temperature.

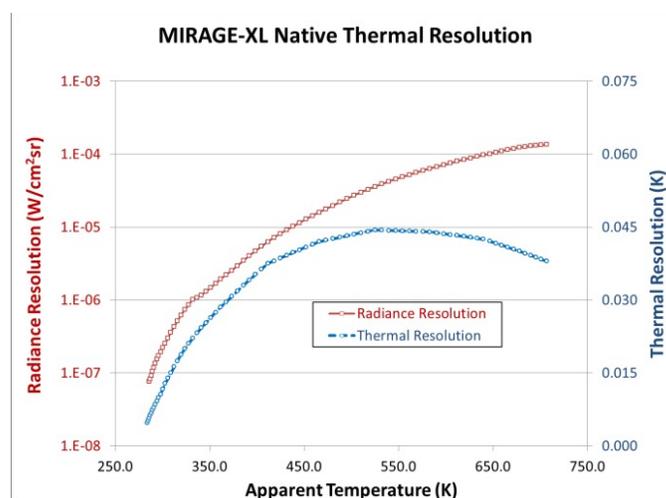


Figure 4. Native thermal resolution of a typical MIRAGE-XL array as a function of apparent temperature. The system has a 16 bit input, but the true resolution is approximately 14 bits due to overlap in the lower and higher bytes of the DACs. The shape is determined by the non-linear transfer function between commanded current and output radiance.

2.1.2 DMD arrays

Another common technology used in infrared scene projection is the digital micro-mirror device or DMD. These devices incorporate an array of small mirrors which can be switched between two positions in order to reflect (“On”) or not reflect (“Off”) radiance from a source. Intermediate temperatures are produced by varying the amount of “On” vs. “Off” time within a single frame period. Assuming a constant illumination source, DMDs have a fairly linear radiance response, with a slight deviation from linear at very low radiance caused by the finite switching time between the two states. Because DMDs use a digital counter to control the duration each individual pixel’s “on” time, the ultimate thermal resolution of the system is limited by the number of DMD clock cycles within the integration time of

the sensor under test. For example, consider a DMD with a mirror switching time of 20 μs being viewed with a gated MWIR sensor operating at 200Hz with a 4000 μs integration time. Such a device could, if the data transfer bandwidth supported it, switch source illumination on and off 50,000 times per second. During the 4000 μs integration time, the mirror could have 200 states if it were switched at its maximum rate, or roughly 8-bit performance. For longer integration times, i.e. lower frame rates, the resolution can improve, even to 14 or 16-bit performance for sufficiently low frame rates. Consider the best case with a DMD capable of 16-bit performance with a source capable of producing a 1500K apparent temperature. A source with a MWIR apparent temperature of 1500K produces an integrated radiance of 2.47 $\text{W}/\text{cm}^2\text{sr}$. With 16-bit performance, a DMD would break this into 65535 steps of $3.77 \times 10^{-5} \text{ W}/\text{cm}^2\text{sr}$. One step of this size would be the equivalent of a 5K step at 300K. Such a step size would be more than 100X the noise floor of even a poor MWIR imager and thus undesirable for depicting a typical terrestrial scene. Thermal resolution would improve at higher apparent temperatures, achieving 8mK at 1500K. Figure 5 shows the radiance response (5a) and thermal resolution (5b) for a DMD in both radiance and apparent temperature.

The DMD example above shows some of the danger in specifying system resolution in terms of just bit depth. At first glance, 16-bit performance may appear to be a good requirement, perhaps even better than the 14-bit performance of the resistive array example given previously. However, a close inspection of the requirement in both radiance and apparent temperature show that a 16-bit system with a linear radiance-to-input response can produce an undesirably poor thermal resolution at terrestrial or lower apparent temperatures.

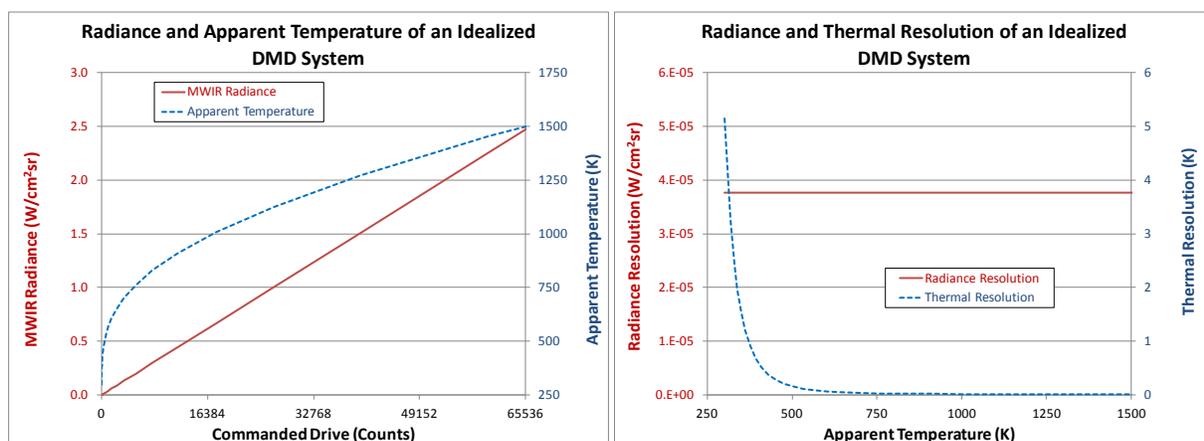


Figure 5. Radiance, apparent temperature and resolution of an idealized DMD projector. The plot on the left (5a) shows the relationship between commanded drive, radiance and apparent temperature for a DMD capable of achieving a MWIR apparent temperature of 1500K. The plot on the right (5b) depicts the radiance and thermal resolutions for the same DMD as a function of apparent temperature.

2.1.3 LED Arrays

A third emitter technology, currently being developed, is that of IRLED arrays. IRLED arrays have not yet been as widely-fielded as resistive arrays and DMDs. IRLEDs are similar to resistive arrays in that individual pixels are driven to directly produce output radiance from each element, as opposed to reflecting radiance from a fixed source. They differ, however, in that the radiance vs. current curve of a typical IRLED at low currents is much more linear than that of a resistive array [4,7], and for this reason, their thermal resolution behavior is similar to that of DMDs.

In order to overcome the inherent resolution limitations of a system with a linear response, one might consider moving to an analog system that allows continuous variation of the input drive. In fact, analog RIICs are used in some resistive arrays as well as in some IRLED arrays. However analog RIICs still have practical limits on the resolution

they can achieve. IRSPs with continually varying analog inputs require the digital imagery from the scene generator to be converted to analog voltage levels through the use of a Digital to Analog Converter (DAC). DAC settling time and resolution specifications, circuit bandwidth, noise floor and system complexity create a trade space that limits the ultimate performance of the projector. Settling time along with the projector size and update rate determine the number of DACs and cabling complexity of the system. A 16 bit DAC may be thought of as having true 16 bit resolution and settling time to 1 bit, but this is often not the case. This appears to be especially true for DACs marketed for RF applications since the absolute DC accuracy is not an issue in RF applications. Unfortunately the vast majority of DACs with extremely fast update rates fall into this category. While these DACs have fast update rates for the digital input ports, often over 1GHz for a 16 bit input, they take several hundred nanoseconds to settle to 1 bit if they are capable of settling to that accuracy at all. The present generation of resistor arrays typically supports frame sizes of 1024 x 1024 with an update rate of 200 Hz, DACs available at the time these systems were designed were capable of settling to 1 bit with 14 bits of resolution in about 500ns. To achieve this 500ns settling time the DAC output has to have a circuit bandwidth of in the neighborhood of 10MHz, bandwidth directly correlates with circuit noise and limits the resolution. High end digital oscilloscopes are a good measure of the achievable analog circuit noise performance as the analog amplifiers on the front end of these scopes are designed by engineers that have many years of experience and are experts in the field of analog circuit design. A designer or engineer involved in the procurement of such a system should be wary of a system that requires noise performance better than high end scopes available today. Most scopes have a bandwidth setting near the 10MHz required by the present generation of analog electronics used with resistive arrays. A noise floor of around 30 microvolts RMS is typical in this bandwidth with the input shorted to remove all noise external to the scope. Opening up the bandwidth of the scope by increasing the bandwidth setting increases the noise and illustrates the challenge that all analog designers of low noise circuits face. An analog input system with performance comparable to a high end scope using a 4 V swing and no external noise would have a maximum bit depth of 17. The achievable noise floor is further degraded by the need to transmit the analog signals over reasonable length cables as shielding from high frequency noise becomes an issue. It is possible to minimize the cable length in some systems that can support having the analog drive electronics close the RIIC but in cryogenic or flight table applications this may not be possible. These issues limit the realistic RIIC analog input performance, and the actual performance of the current analog input electronics is approximately 14 bits. Thus, moving to an analog RIIC would not be an effective way to improve the low-temperature thermal resolution of a system with a linear emitter response, such as that of a typical IRLED.

2.2 Preprocessing Electronics

One step upstream in the signal chain from the emitter array are the preprocessing electronics. For resistive arrays these electronics are often referred to as the command and control electronics (C&CE) or PC-base Array Control Electronics (PACE). These electronics take the digital image data output by the scene generator and format it for input to the emitter array's drive electronics. For example, a scene generator might output a scene as a rastered image using DVI, while the emitter array might require the image data to be distributed across parallel digital inputs. The preprocessing electronics would therefore have to appropriately parse and buffer the incoming data stream, and then reformat it for output to the emitter. The preprocessing electronics may in some cases also perform other digital image processing, including:

- Non-uniformity correction (NUC) to ensure that all pixels respond in a uniform manner
- Global gain and offset transformations to change radiance values for test or scaling purposes
- Global linearization to modify the radiance versus drive curve of the system to simplify upstream processing
- Translate/rotate processing (TRP), used in conjunction with oversized images to mitigate latency in the scene generation system
- Convolution and other spatial processing, such as two-color spatial correction

These preprocessing steps have some interactions which may affect the thermal resolution of the overall system, and which may in turn be affected by the system's thermal resolution. The NUC can be limited by the thermal resolution at a given point. For example, if the thermal step at a given radiance level is 5% of the measured radiance, then the NUC correction will be limited to 5% steps, so achieving a corrected non-uniformity much less than 5% will not be possible. Global linearization is another algorithm commonly implemented in the preprocessing electronics. This algorithm may adversely affect system thermal resolution. Global linearization is often used to simplify upstream data processing by making an emitter with a nonlinear response, such as a resistive array, appear linear in radiance to other parts of the system, such as the scene generator. This allows all upstream processing to be linear in radiance instead of having to accommodate a nonlinear response of the emitter. Spatial processing algorithms such as TRP, convolution, and distortion corrections are much easier to implement if they operate in linear radiance units. Without linearization, each algorithm would have to transform the incoming and outgoing data in accordance with the nonlinear emitter response. This makes linearization a desirable algorithm to have in the preprocessing electronics. However, the application of linearization then limits the system to the step size of that linearization. This can be demonstrated in the following example. Consider an IRSP based on a resistive array which requires TRP and thus needs to implement global linearization. The system's native response is measured and then a lookup table is generated such that incoming steps in the commanded drive produce equally spaced steps in radiance. Figure 6 shows how a linearization works in principle. For the MIRAGE and PACE based systems, the preprocessing electronics occurs in a 16-bit fixed point format. Thus, the table input is an integer from 0 to 65535 and the table output is a curve with approximately 16000 (14-bit) unique values. Since the native output is not linear, the values are not evenly spaced, as can be seen in the output drive of the lookup table shown in Figure 6. The result is a loss of thermal resolution at low apparent temperatures. Figure 7 shows the thermal resolution of a resistive array that has been linearized. Both the thermal resolution of the 16-bit linear input and the native resolution of the emitter array are shown. The system resolution at a given apparent temperature is governed by the larger of the two thermal step sizes.

Specifying requirements for preprocessing electronics can be complex due to the non-linear output of the emitter array which it is designed to support. On the surface, requiring 16-bit support in the preprocessing electronics may appear sufficient for an emitter with an effective 14-bit input. However, as the example above demonstrates, this can still lead to the preprocessing electronics being the limiting factor in the system. If the emitter array has a nonlinear response either inherently, or by specific design, the preprocessing electronics must be designed to work with that nonlinearity to support the highest fidelity of which the emitter array is capable. Note that the loss of thermal resolution described above will become more pronounced as the maximum radiance increases. To prevent this from becoming a significant limitation, future preprocessing electronics for high temperature resistive arrays will need to implement a higher-resolution format (such as 24-bit fixed or a floating point representation).

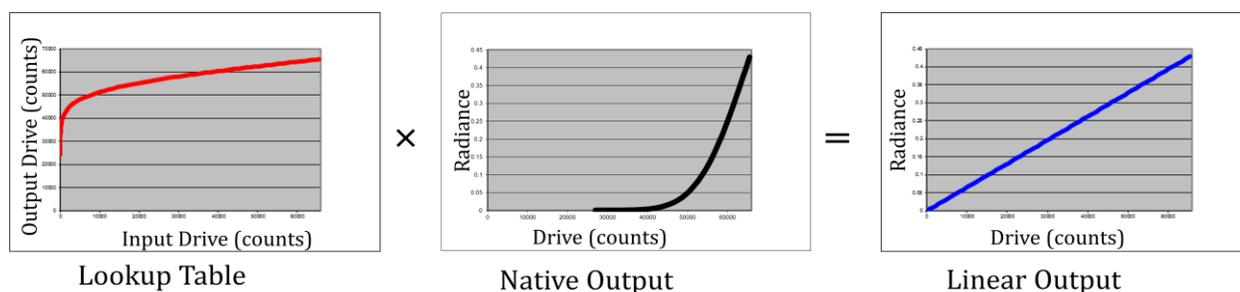


Figure 6. Principle of digital linearization. The native radiance output of an emitter is measured (center plot). From those measurements, a lookup table is generated (left plot). Incoming emitter drive commands pass through the lookup table which compensates for the nonlinear emitter output, thus producing linear radiance as a function of commanded drive (right plot).

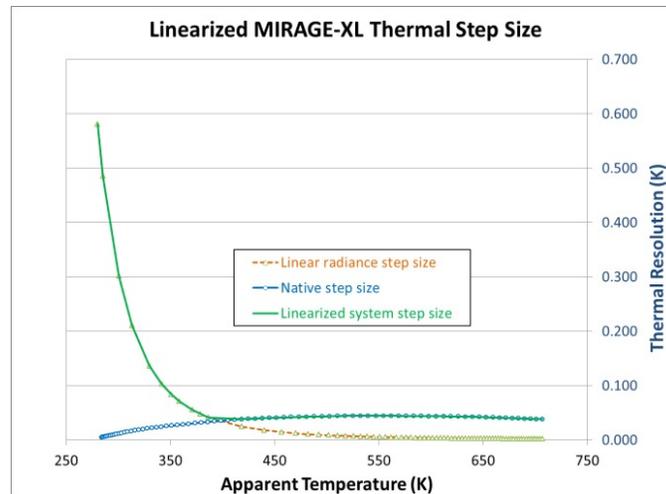


Figure 7. Thermal resolution of a resistive array after digital linearization. The blue curve with circular markers shows the native resolution of the resistive emitters. The orange dashed line shows the thermal resolution of the constant radiance step as a function of apparent temperature. Note that its shape is similar to that of the linear DMD in Figure 5. The green straight line shows the system thermal resolution, which is governed by the larger of the two steps at any given apparent temperature.

2.3 Scene Generation System

The scene generation produces the simulated images to be projected by the emitter. In order to support the emitter, the scene generator must be capable of performing radiance calculations with sufficient thermal resolution. As the dynamic range of the emitters increases, this may preclude the use of some integer-based rendering algorithms. Many, if not all, state-of-the-art scene generation systems already use floating point calculations in their rendering algorithms, so calculation precision should not be a limiting issue in the future. That said, as discussed in section 2.2, the scene generator must transfer the scene data using a protocol that supports sufficient numerical precision to avoid being a limiting factor in the overall system thermal resolution. Most current systems use a digital standard, such as DVI to transfer the scene data to the C&CE. These C&CEs, including SBIR's MIRAGE product line and the KHILS PACE systems, operate on a 16-bit fixed point basis, and typically make use of two of the three colors in the DVI data stream. The primary requirement when specifying a scene generator, therefore, is that it supports the input format of the preprocessing electronics.

One thing to keep in mind for future systems is the idea of using the scene generator to simplify the preprocessing electronics. As stated previously, a key reason for implementing the spatial algorithms such as TRP and convolution in the preprocessing electronics was to reduce the computational load on, and address latency in the scene generator. As scene generator systems become faster, the need for incorporating TRP or convolution in the preprocessing electronics diminishes. If all the processing that required linear radiance were removed from the preprocessing electronics, a transform that is nonlinear in radiance could be applied at the scene generator and that transformed data be transferred to the preprocessing electronics. This would remove some of the limits discussed above that are imposed by using linearized radiance. For example, assume a scene generator was capable of rendering a scene with a latency of less than a frame time. Instead of sending a number associated with radiance, a different quantity could be selected, such as apparent temperature. If we were to specify that the scene generator output was apparent temperature, the range from 300 to 1500K could be covered using a 16-bit representation with precision better than 20mK. Instead of linearizing in radiance, the preprocessing electronics could use the global table to linearize in apparent temperature. This would lead to good thermal resolution across the entire dynamic range of the emitter array

and still only require 16-bit precision at any point after the initial scene generation. NUC and other preprocessor functions do not require linear radiance and could easily accommodate the change. Allowing the preprocessing electronics to use 16-bit precision would significantly lower their risk and complexity.

3. SUGGESTIONS FOR SYSTEM SPECIFICATION

Proper specification of overall system performance requires that the performance and limitations of each subsystem be considered. In addition, the interaction between subsystems must also be taken into account. In this section, we will discuss the basic needs of the system and subsystems and provide some suggestions for improving thermal resolution requirements specification for IRSPs.

3.1 System

First and foremost, the desired thermal resolution requirements for the overall system need to be determined. This may not always be straightforward, as the high expense of an IRSP system often dictates that it be used to support multiple IR sensors. As previously discussed, a single radiance step size (or a number of bits for the system) will generally not be optimum for an IRSP with a large dynamic range. Practical and conservative requirements for radiance levels, and thermal resolution at those levels, must be developed.

There are multiple ways to go about formulating the system requirement. One way is to specify a total radiance range, and then break that full range up into sections with individual resolution step sizes. Another approach is to use apparent temperature to specify the thermal resolution. A third possibility is to specify relative precision, along with a minimum resolution value (e.g. the larger of 0.1% in radiance or 50mK at 300K). Although it is not technically the actual unit of measurement, the use of apparent temperature is generally much more intuitive. Even if the final requirements are expressed in radiance, converting that radiance and associated resolution requirements to apparent temperature can lead to a “better” requirement, based upon a better understanding of what may or may not be practical. In fact, it is recommended that radiance and resolution requirements be provided in both radiance units and apparent temperature units to help better promote a better understanding of overall system requirements.

3.2 Emitter array

The emitter array is the key component in an IRSP and it will often be the limiting factor for overall system thermal resolution. For that reason, the emitter thermal resolution will simply match that of the system in most cases. Additional pertinent information should also be included in the specification to ensure clarity. These include requirements such as dynamic range within a scene and frame rate. Available performance trade space, such as the ability to sacrifice some thermal resolution at higher frame rates, should be identified if it is not already in the system requirements. Other factors that could affect the emitter array interface, such as cabling distance from the emitter to the preprocessing electronics or scene generator, should be included if it is potentially significant (e.g. intended for use on a flight motion system).

3.3 Preprocessing electronics

The preprocessing electronics must be compatible with both the scene generator and the emitter array. If they are to be procured separately from the emitter array and the scene generator, both interfaces must be specified. If they are to be procured in conjunction with the emitter, then only the scene generator interface must be specified. In either case, the expected emitter response curve must be known so that it can be matched with properly-designed electronics. Any preprocessing algorithms implemented should be included, and any performance trade space identified (e.g. what

reduction in thermal resolution is acceptable if TRP or some other spatial algorithm is employed). The supported scene generator formats must also be specified, including: frame rate, number format and interface protocol, such as DVI.

3.4 Scene Generator

The scene generator is the last subsystem considered here. For the scene generator, the requirement for radiance precision should be given as well as the desired output format and protocol. In order to support radiance ranges for systems capable of MWIR apparent temperatures over 1000K, a fixed point interface with 24-bit precision will be needed. If available, and practical for the preprocessing electronics, a floating point format would be another ideal choice as an interface. The main requirement for the scene generator is that the output format should provide sufficient thermal resolution across the range of the simulation and be compatible with the preprocessing electronics.

4. SUMMARY/CONCLUSIONS

Specifying the various subsystem requirements for an IRSP such that they ensure the desired end-system thermal resolution can be challenging. This is particularly true when the component subsystems are procured from multiple vendors and not as a fully-integrated 'turnkey' system. While specifying a particular bit depth for a system or subsystem is common, such an approach can lead to insufficient thermal resolution in some cases. If requirements do not take into account the expected radiance response, a bit depth specification may compromise the thermal resolution of an IRSP at low apparent temperatures. An improved method of stating requirements has been suggested which includes specifying the desired thermal resolution as a function of the output radiance, and stating output radiance and thermal resolution in both radiance and apparent temperature units. Subsystem requirements should flow from the system requirements and accommodate interactions with the other subsystems and their signal processing to avoid the introduction of additional limits on system thermal resolution.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

- [1] J. Oleson, J. James, J. LaVeigne, K. Sparkman, G. Matis, S. McHugh, J. Lannon, S. Goodwin, A. Huffman, S. Solomon, P. Bryant, "Large format resistive array (LFRA) infrared scene projector (IRSP) performance and production status," *Proc. SPIE*, vol. 6208, 2006.
- [2] K. Sparkman, et al., "Ultra high temperature (UHT) infrared scene projector system development status," *Proc. SPIE*, vol. 8356, 2012.
- [3] D. B. Beasley, M. Bender, J. Crosby, S. McCall, T. Messer, D. A. Saylor, "Advancements in the Micromirror Array Projector Technology II," *Proce. SPIE*, vol. 5785, 2005.
- [4] D. T. Norton, J. T. Olesberg, R. T. McGee, N. A. Waite, J. Dickason, K. W. Goossen, J. Lawler, G. Sullivan, A. Ikhlassi, F. Kiamilev, E. J. Koerperick, L. M. Murray, J. P. Prineas, and T. F. Boggess, "512 × 512 Individually

Addressable MWIR LED Arrays Based on Type-II InAs/GaSbSuperlattices," *IEEE J. Quant. Electron*, vol. 49, 2013.

- [5] S.Jung, S.Suchalkin, D.Westerfeld, G.Kipshidze, E.Golden, D.Snyder, G.Belenky, "High dimensional addressable LED arrays based on type I GaInAsSb quantum wells with quinternary AlGaInAsSb barriers," *Semicond. Sci. and Tech.*, vol. 26, no. 8, 2011.
- [6] K. Sparkman, et al., "Ultrahigh-temperature emitter pixel development for scene projectors," *Proc. SPIE*, vol. 9071, 2014.
- [7] D. T. Norton, Type-II InAs/GaSbsuperlattice LEDs: applications for infrared scene projector systems, 2013.