MIRAGE

DYNAMIC INFRARED SCENE PROJECTOR

Frequently Asked Questions

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What is the output temperature range of MIRAGE?

In the 3-5μ band, the MIRAGE emitter's radiometric temperature range is 17°C to 450°C.

In the 8-12μ band, the MIRAGE emitter's radiometric temperature range is 15°C to 314°C.

What is meant by "radiometric temperature"?

The radiant exitance from a pixel will be determined by the temperature of the pixel's emitting surface, attenuated by fill factor, emissivity, etc. So this pixel appears to be at some lower temperature, called the "radiometric temperature". An ideal blackbody at that radiometric temperature would emit the same in-band radiance as this pixel.

Is MIRAGE a Long Wave IR or Mid Wave IR device?

The MIRAGE pixels are broadband emitters. The window on the dewar that houses the emitter is chosen to provide high (>95%) transmission MWIR (3-5μ) or LWIR (8-12μ). A broadband (3-14μ) window is also available.

Why is the temperature range 3-5μ different from 8-12μ?

The individual pixels that comprise the MIRAGE emitter are not ideal blackbodies (emissivity = 1), or even ideal graybodies (emissivity constant at all wavelengths). The effective emissivity and radiance in the 3-5μ band is different from that in the 8-12μ band, so at any setpoint, a pixel appears to be at different temperatures in the two wavebands.

What's the math behind the calculation of radiometric temperature?

Planck's law describes the spectral radiant emittance of an ideal blackbody as a function of its temperature.

$$M(T) = \int_{\lambda_2}^{\lambda_1} w(\lambda)\,d\lambda$$, where

$$w = \frac{c_1}{\lambda^5} \cdot \frac{1}{e^{\frac{c_2}{\lambda \cdot T}} - 1} \qquad c_1 = 3.77417749 \times 10^{-4} \frac{W}{cm^2} \mu^4 \qquad c_2 = 1.438769 \times 10^4 \mu \cdot K$$

A pixel-based scene generator, however, is not an ideal blackbody. The characteristics that will affect its radiant output are:

Symbol	Parameter	Typical value
F	fill factor	.46
ε_p	emissivity of pixel	.75
ε_s	emissivity of substrate	.20
τ	optics transmittance	.94
T_s	temperature of substrate	0°C
T_a	ambient temperature	25°C
T_p	temperature of the pixel	0-650°C

The radiant exitance from a pixel will be determined by its temperature T_p, attenuated by fill factor, emissivity, ambient effects, etc. So that pixel appears to be at some lower temperature, the "radiometric temperature". An ideal blackbody at this radiometric temperature would emit the same radiance as the pixel at temperature T_p.

More specifically, the total radiant exitance from the pixel will come from several sources:

a) Radiation from the emitting surface of the pixel, as attenuated by the fill factor and emissivity of the pixel, and the transmittance of the optics.
   $[F \cdot \varepsilon_p \cdot \tau \cdot M(T_p)]$
b) Radiation from that portion of the substrate visible behind the pixel, as attenuated by the substrate's emissivity and the transmittance of the optics.
   $[(1-F) \cdot \varepsilon_s \cdot \tau \cdot M(T_s)]$
c) Reflection from the emitting surface of the pixel, as attenuated by the fill factor and reflectance of the pixel, and the transmittance of the optics.
   $[F \cdot (1-\varepsilon_p) \cdot \tau \cdot M(T_a)]$
d) Reflection from that portion of the substrate visible behind the pixel, as attenuated by the substrate's reflectance, and the transmittance of the optics.
   $[(1-F) \cdot (1-\varepsilon_s) \cdot \tau \cdot M(T_a)]$
e) Radiation plus reflection from the optics.
   $[(1-\tau) \cdot M(T_a)]$

Combining each term above yields an expression for total radiance from the pixel:

$$M_{net} = [F \cdot \varepsilon_p \cdot \tau \cdot M(T_p)] + [(1-F) \cdot \varepsilon_s \cdot \tau \cdot M(T_s)] + [F \cdot (1-\varepsilon_p) \cdot \tau \cdot M(T_a)] + [(1-F) \cdot (1-\varepsilon_s) \cdot \tau \cdot M(T_a)] + [(1-\tau) \cdot M(T_a)]$$

$$= F \cdot \varepsilon_p \cdot \tau \cdot M(T_p) + (1-F) \cdot \varepsilon_s \cdot \tau \cdot M(T_s) + [1 - F \cdot \varepsilon_p \cdot \tau - (1-F) \cdot \varepsilon_s \cdot \tau] \cdot M(T_a)$$

Now, define a function $M^{-1}(x)$, the inverse of $M(x)$. In other words, $M(T)$ uses temperature to compute radiance, and $M^{-1}(x)$ uses radiance to compute temperature. So $M^{-1}(M(T)) = T$.

From the definition of radiometric temperature,

$$\text{Radiometric temperature} = M^{-1}(M_{net})$$
$$= M^{-1}\{ F \cdot \varepsilon_p \cdot \tau \cdot M(T_p) + (1-F) \cdot \varepsilon_s \cdot \tau \cdot M(T_s) + [1 - F \cdot \varepsilon_p \cdot \tau - (1-F) \cdot \varepsilon_s \cdot \tau] \cdot M(T_a)\}$$

Using the typical values listed in the table above, the effective temperature range of the scene can be computed.

3-5μ, T_p = 0°C: Radiometric temperature = 17°C
3-5μ, T_p = 650°C: Radiometric temperature = 450°C

8-12μ, T_p = 0°C: Radiometric temperature = 15°C
8-12μ, T_p = 650°C: Radiometric temperature = 314°C

So in the 3-5μ band, the MIRAGE emitter can simulate a blackbody with a temperature range of 17°C to 450°C. In the 8-12μ band, the MIRAGE emitter's effective temperature range is 15°C to 314°C.

Some of the assumptions in the above calculations: All reflected energy, as well as the temperature of the optics, is at T_a (25°C). Optics transmittance of 94% is the throughput of a wideband window in the dewar. If a collimator or other optical system is used with MIRAGE, then τ, and therefore radiometric temperature range, will be lower.

The maximum T_p is derived by dividing the maximum power delivered to a pixel by the thermal conductance to the emitter substrate: 1.8×10^{-4} W / (2.4×10^{-7}W/K) = 750K above substrate temperature. This temperature rise is reduced to 650K to allow for non-uniformity correction and for other process variations. A substrate temperature of 0°C then places maximum pixel temperature at 650°C.

Can the lower temperature limit of MIRAGE be extended?

Yes, but not easily. It would seem that the most direct way to lower the minimum radiometric temperature of the array would be to lower the substrate temperature, and therefore the minimum pixel temperature. However, since the predominant contributor to radiant exitance at the low end is *reflected* ambient radiation, lowering the *radiated* component will have little effect. If the substrate temperature and pixel temperature are lowered from 0°C to -40°C, the radiometric temperature is lowered only by 4°C in the 3-5μ band, and by 7°C in the 8-12μ band.

To lower the minimum temperature significantly requires that the reflected ambient radiation be reduced: low-temperature environment, cooled optics, etc. This is more a function of the system installation than of the MIRAGE emitter itself.

Is the radiometric output affected by ambient temperature?

Yes. Since the fill factor and the emissivity are less than unity, a portion of the radiant exitance from the emitter surface will be reflected energy from the environment. The effect on radiant exitance (and radiometric temperature) of a 1°C change in environment temperature is given in the table below.

	3-5μ	8-12μ
Radiometric temperature = 300K	2% (.56°C)	1% (.58°C)
Radiometric temperature = 500K	.02% (.02°C)	.1% (.20°C)

What is the rise time of a MIRAGE pixel?

In MIRAGE, rise time is a function of frame rate. At the system's maximum frame rate of 200 Hz, or at some sub-multiple of that frame rate (100 Hz, 66 Hz, 50 Hz, etc.), rise time (0 to 90% of setpoint temperature change) is approximately 5 milliseconds.

How is "rise time" different from "time constant"?

The natural time constant of a MIRAGE pixel is 5 milliseconds. That is, if a step change in control voltage is applied to a pixel, it will reach 63% of its new steady state temperature in 5 milliseconds, 87% in 10 milliseconds, 95% in 15 milliseconds, etc.

If rise time is defined as the time it takes temperature to move from 10% to 90% of its setpoint change, then this will occur in 2.3 time constants, or about 11 milliseconds, if temperature is allowed to rise in its normal exponential fashion.

However, in MIRAGE, an "Overdrive" algorithm is implemented to reduce the pixel's rise time. With this algorithm in place, rise time 0-90% is reduced to as little as 5 milliseconds.

Frame rate in MIRAGE is 5 milliseconds. Time constant is 5 milliseconds. Rise time is 5 milliseconds. Are these all the same thing?

No. It is appropriate that these quantities be of the same magnitude, but they are not synonymous.

The frequency with which the image is refreshed or changed is the frame rate. MIRAGE can write new images at 200 Hz, yielding a 5 millisecond frame time. Frame rate is limited by the speed of the on-chip electronics, and of the electronics processing the pixel data.

Time constant is independent of frame rate. Just because a new frame is written to the emitter every 5 msec doesn't mean that the pixel can change temperature fast enough to take advantage of this new image. (It should, and in MIRAGE it does, but in theory a system could be designed with a frame rate that outstrips the time constant, or vise versa.) Time constant is determined by the thermal mass of a pixel, and by the rate at which heat can be transferred to the heatsink. Strictly speaking, time constant is a mathematical characteristic of an exponential curve: in one time constant, a function will cover 63% of the distance to its steady state value.

Rise time and time constant are closely related. *Rise time* is frequently defined as the time it takes for temperature to rise from 10% to 90% of its steady state value. Other definitions are sometimes used: 0% to 90%, etc. Recall that *time constant* is the time that it takes a simple exponential function to rise from 0% to 63% of its steady state value. So for a system with a simple step input, it takes 2.3 time constants to move from 10% to 90%. However, in MIRAGE, power is not applied as a simple step input, but instead it is applied in such a manner as to drive temperature to its steady state value in one frame period (5 msec). This rise time enhancement is called "Overdrive".

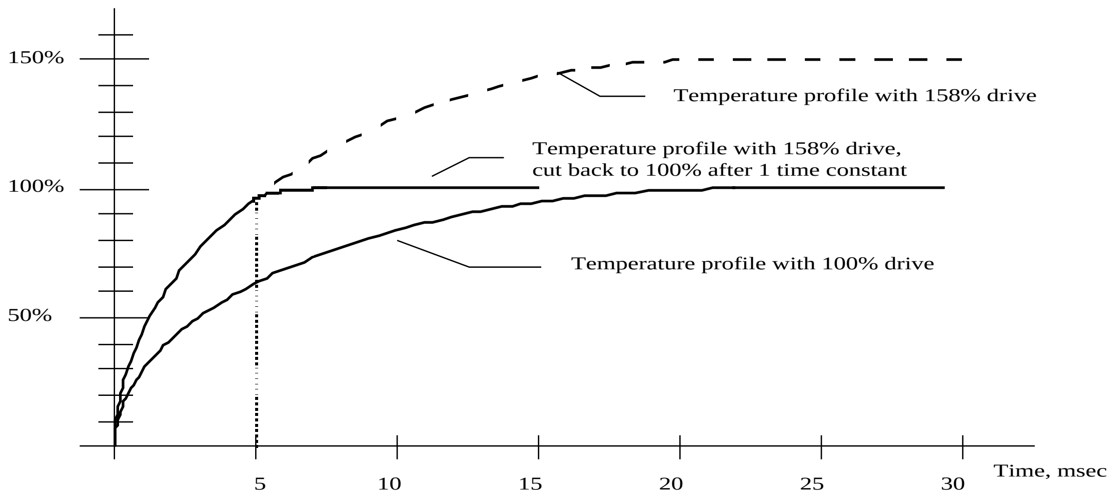
Does radiance have the same 5 millisecond time constant as temperature?

No. Since radiance is a high-order function of temperature, it will rise more slowly and fall more quickly than temperature. This difference in speed is both wavelength-dependent and temperature-dependent.

This effect is not a feature (or defect) of the MIRAGE emitter, but comes straight from Planck's Law. It is true of any blackbody radiator.

How does Overdrive improve rise time?

If a step change in control voltage is applied to a pixel, it will reach 63% of its new steady state temperature in 1 time constant (5 msec in MIRAGE). If instead we drive the pixel with 158% of the change in setpoint (not of the setpoint, but of the change in setpoint), then in 1 time constant it will reach the setpoint temperature. At this point in time, the drive voltage is cut back to its steady state value, or the temperature would rise 58% more than intended. Graphically, this is how temperature slew will look:



The overdrive voltage and timing are such that the pixel will be within 10% of its new setpoint temperature in 1 time constant. After that, it will settle to its steady state value at the $e^{-t/\tau}$ exponential rate, with a 5 msec time constant.

The drive voltage is updated once per frame. Since maximum frame rate and time constant are both 5 msec in MIRAGE, the 158% overdrive value is appropriate for a 200 Hz frame rate, or some sub-multiple of that rate (100 Hz, 66 Hz, 50 Hz, etc.). For other frame rates, the overdrive ratio is adjusted appropriately, and the rise time will be equal to the highest multiple of that frame rate which is less than 200 Hz. For example, with a 60 Hz frame rate, rise time will be 1/(3· 60 Hz) = 5.55 msec.

Can Overdrive improve temperature fall time as well as rise time?

Yes. Just as a larger-than-steady-state voltage will accelerate a positive temperature change, a smaller-than-steady-state voltage will accelerate a negative temperature change. Obviously, if the new setpoint is at the minimum achievable temperature, there is no overhead available to create this overdrive (or, perhaps more aptly, underdrive) voltage. But for negative temperature changes to some point other than minimum temperature, fall time can be improved with Overdrive.

What are the limitations of Overdrive in improving rise time?

Since overdrive relies on briefly applying a voltage greater than the steady state value, there will be times when overdrive can't be used. A *large* change to a temperature near the limit (either high or low limit) will not have available overhead to create the overdrive signal. This will not be a problem for *small* changes from one temperature near the limit to another temperature near the limit.

Misconception: Overdrive cuts the frame rate in half.

Overdrive applies the higher pixel voltage for one frame and then the steady-state voltage in the following frame. However, this doesn't really halve the frame rate. Consider what a 200 Hz frame rate means: a new feature can begin to appear, move, or disappear every 5 ms. Another way of stating it is that any pixel can start a transition to a new temperature every 5 ms. This capability is unaffected by the presence or absence of overdrive -- new pixel information is sent to the emitter every frame (every 5 ms.). All that overdrive does is provide extra power so that a pixel reaches its new steady-state temperature in one frame, rather than allowing it to slew toward that temperature in a simple exponential fashion.

Misconception: The MIRAGE emitter needs a two-stage cooler to function properly.

Actually, MIRAGE can be cooled quite adequately with a simple refrigerated bath. In the standard MIRAGE installation, however, additional temperature control hardware is added to improve the thermal stability of the emitter substrate. This is not a two-stage cooler, but rather an inner temperature control loop to improve temperature stability beyond that achievable with the refrigerated bath alone.

The result is more accurate and more stable control of the emitter substrate, and thus of the projected scene. In some applications, this additional control accuracy may not be necessary, but it is available.

Why is accurate control of the substrate temperature important?

The temperature of each pixel is set by applying a defined amount of power to that pixel. This drives the pixel a known delta above the substrate temperature. If substrate temperature changes, pixel temperature will change with it. An inaccurate substrate temperature will not significantly affect the scene's temperature contrast, but it will affect the scene's absolute temperature accuracy and radiance contrast.

Misconception: The MIRAGE emitter dissipates so much power that it is difficult to apply.

From a user's standpoint, cooling issues have already been taken care of by the supplier, Santa Barbara Infrared. The Digital Emitter Engine (DEE), in which the emitter is installed, includes a heatsink with appropriate thermal capacity to cool the emitter. Cooling fluid to the heatsink is supplied by an external refrigerated bath, which is normally delivered as part of the Thermal Support System (TSS).

In applications where the user supplies his own cooling, a number of compact, inexpensive, commercial off-the-shelf chillers are available which can readily cool the heatsink. The emitter chip dissipates about 120 watts in its Constant Power mode, and much less (<5 watts for a typical scene) in Power-On-Demand mode.

The DEE is designed for ease of application. It contains all necessary support for the emitter: a vacuum dewar with a heatsink, the close support electronics (fiber optic receiver, power supply regulation, etc.) and a 3-point kinematic mount. The complete DEE is approximately 9" diameter x 12" long, and weighs 14 pounds.

Why does the MIRAGE emitter dissipate so much power?

The MIRAGE emitter can operate in two modes: constant power mode, or power-on-demand mode. Constant power mode eliminates thermal and electrical cross-talk, improving the integrity of the projected scene.

In constant power mode, pixel current is directed either into the emitter resistor or into an on-chip dummy resistor, so that current to each pixel is constant, regardless of the programmed pixel temperature. In constant power mode, the emitter dissipates approximately 120 watts. The Digital Emitter Engine's heatsink and the Thermal Support System's refrigerated bath can handle this power continuously.

For applications where power dissipation must be minimized, the emitter can be operated in its power-on-demand mode. In this mode, pixel current is not diverted to the on-chip dummy resistor, so emitter power consumption is now scene-dependent, and would reach 120 watts only with a uniform scene at maximum temperature. A more typical scene would dissipate less than 5 watts. The thermal and electrical design of the emitter minimize the secondary effects of this variable power consumption (busbar robbing, thermal spreading, etc.), but not to the extent that these effects are attenuated in constant power mode.

Can the MIRAGE emitter be modified to use less power?

No modification is necessary -- it already has this capability. The MIRAGE emitter can operate in two modes: constant power mode, or power-on-demand mode. In power-on-demand mode, the emitter would dissipate less than 5 watts to render a typical ground-based scene.

What is the production yield of the MIRAGE emitter array assembly?

Although we grow 44 ICs on each wafer, each wafer yields 16 usable ICs due to dicing requirements associated with our current 2-IC by 2-IC hybridization process. Once the wafer is out of the foundry, each of the 44 IC's are tested. Yield at this point is 87%. Sixteen of the best ICs are selected based on operability and dicing geometry. Using our previous experience with TTFM and our initial production runs with the emitter array, it is estimated that two ICs will be lost to scrap in the TTFM process, and that of the remaining fourteen hybrids seven will be fully operable. This results in a yield of 44%: seven good emitter arrays out of the 16 ICs available after the initial dicing of the wafer.

Currently, the hybridization process builds up a 2 x 2 section of the wafer. As the process moves to 3 x 3 and eventually to hybridization of the full wafer, yields will rise as losses due the dicing are eliminated.

TTFM: What is it and what are its advantages?

The Transfer Thin Film Membrane (TTFM) process is a proprietary technique allowing attachment of an array of thin resistive elements (pixel emitters) onto the upper surface of an IC. This attachment provides thermal and electrical conductivity as well as control of radiometric features of the resistor and its underlying absorber and reflector. Because much of the resistive element is fabricated prior to hybridization to the underlying IC, the resistive array can be annealed at high temperatures (950°C) without exposing the IC to these high temperatures. This annealing process reduces internal mechanical stresses and stabilizes emissivity, avoiding problems which can occur in un-annealed emitters, or in emitter annealed at low temperatures.

Another advantage to TTFM is that poorly formed or defective resistive arrays are not attached to the valuable underlying IC. This results in less production risk and higher yields. The TTFM process also has the less obvious advantage of being tied to advances in micro-bolometer development, providing continuous updating of the technology used to produce these micro-emitters.

How can only two on chip DACs keep up with MIRAGE throughput rates?

Each of MIRAGE's precision on-RIIC 16 Bit DACs convert at 28 Mwords/second. These very high speeds, and the high dynamic range, are possible by using a proprietary Indigo Systems design. The on-chip placement results in very low capacitive load, and coupled with other unique design features, results in much higher speed operation against the reduced parasitic loads. To maintain the 200 Hz frame rate, the DAC rise time and fall time should be less than 37 nanoseconds. Test data shows the measured values as 19 and 18 nanoseconds, respectively.

How do the emitter bond wires handle the required current/power?

The emitter bond wires on MIRAGE are 0.0013 inch diameter gold wire. According to our wire supplier these wires are rated at 0.6 amps per wire. MIRAGE uses 200 wires to bring power into the array, giving it a current capacity of 120 amps. The maximum current supplied to the emitter is 30 amps, resulting in a four to one safety factor for delivered power.

How is Minimum Effective Temperature Resolution determined?

Minimum Effective Temperature Resolution (METR) is expected to be approximately 0.004°C at emitter radiometric temperature of 22°C, and 0.024°C at emitter radiometric temperature of 300°C. These values were derived from models that applied the relevant emitter array design parameters to the question of METR. Many of these design parameters have been verified through test, including emitter time constant, thermal conductivity, resistance and temperature coefficient of the emitter, voltage output range of the RIIC DACs, and DAC LSB step size.

Initial measurements of METR are being conducted now. A preliminary data point is that the 9th DAC bit yields resolution of 0.02°C at 10°C, implying sufficient resolution at 14.5 bits, the specified DAC linearity limit. At present, emitter non-uniformity and camera sensitivity limit measuring METR with higher accuracy.

What is the maximum frame rate?

The maximum internal frame rate is 200 Hz. The Command and Control Electronics (C&CE) can be configured so that inputs with slower frame rates (0 to 100 Hz) can be sent to the emitter at a multiple of the input frame rate. For example, a 30 Hz input can be written to the emitter at 180 Hz.

What synchronization capabilities are available?

The customer can supply a wide variety of sync signals. The External Sync input uses a Lucent Technologies Differential Receiver BRR1A. The preferred transmitter from the user would be the Lucent Technologies BDP1A Differential Transmitter or equiv. Provision in the C&CE can customize signal levels to the customer's input.

MIRAGE can be slaved to a sync signal from either UUT or the scene animation software; or MIRAGE can be the master, supplying sync to the UUT and scene animation software.

MIRAGE accommodates the Silicon Graphics DVP2 Genlock interface.

Can the user open up the DEE dewar?

No. Because of the complexity and fragility of the components within the dewar all service on it must be performed at SBIR.

What is the distance between various components of the MIRAGE system?

In the standard MIRAGE configuration, the following are typical distances:

The System Controller to the C&CE …………….……………………………. 25 ft
C&CE to the DEE …….…………………………………………………… up to 450 ft

TSS to the DEE ……………………………………………………………… 33 ft
CRS to the DEE ……..……..… (during calibration the DEE is mounted on the CRS)
CRS to System Controller ………………………………………………………… 25 ft

C&CE: Command and Control Electronics
DEE: Digital Emitter Engine
TSS: Thermal Support Subsystem
CRS: Calibration Radiometry Subsystem

These distances can change to accommodate customer requirements.