FLIR Lepton Radiometry Application Note

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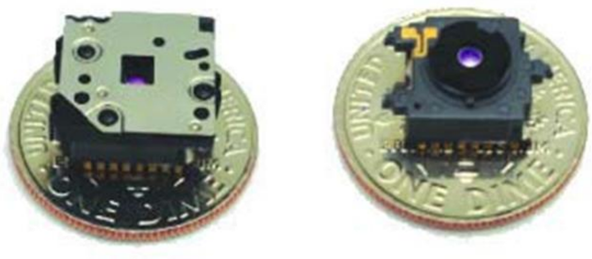


Table of Contents

1 Document

Revision History

Version	Date	Comments
100	Oct. 17, 2014	Initial Release

Scope

This document describes the calibration and external processing required to convert the temperature-stabilized output of Lepton to scene temperature. It is divided into 6 sections:

- Flux-to-temperature conversion: describes the basic equations required to convert between scene flux and scene temperature.
- Compensation for scene factors: describes the basic equations required to correct for scene factors such as target emissivity, background temperature, etc.
- Radiometric calibration: describes the calibration process used to generate the terms used in the flux-to-temperature / temperature-to-flux conversion process.
- FFC: describes the flat-field correction (FFC) process and the radiometric implications of FFC.
- Sources of error: describes the ideal conditions for radiometric conversion and describes sources of radiometric error.
- Frequently-asked questions: largely a repeat of the contents of the first five sections in a FAQ format.

Flux-to-temperature Conversion

When radiometric mode is enabled, the 14-bit video from Lepton is stabilized and normalized such that a scene with a given temperature will nominally correspond to a particular digital value in the video stream, independent of Lepton's own temperature. The signal from the camera, denoted as *S,* is called flux-linear because it is linear to the radiometric flux within Lepton's spectral band. The flux-linear signal is related to scene temperature by the Planck curve:

$$S = W(T_K) = \int_{\lambda 1}^{\lambda 2} \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp(ch/\lambda k T_K) - 1} \Re(\lambda) \bullet \delta\lambda ,$$

Equation 1

where S is the output signal, $\lambda 1$ and $\lambda 2$ define the spectral band, h is Planck's constant, k is Boltzmann's constant, c is the velocity of light, R(λ) is the camera responsivity (as a function of wavelength), and T_K is absolute temperature in units of Kelvin. Since Equation 1 is impractical to calculate in software, the temperature-to-signal conversion is typically approximated by the so-called RBFO equation:

$$S = W(T_K) = \frac{R}{\exp(B/T_K) - F} + O ,$$

Equation 2

where S is the output signal; R, B, F, and O are parameters generated during calibration; and T_K is absolute temperature. The conversion from flux to temperature is performed using the inverse of Equation 2:

$$T_K = B / \ln\left(\frac{R}{S_R - O} + F\right) .$$

Equation 3

In general, compensation for emissivity and other external parameters is performed before applying flux-to-temperature conversion, as described in the Section 0.

In some processing systems, it may not be practical to calculate exponentials and logarithms in real-time; in such cases, equations 2 and 3 are often implemented as look-up tables (LUTs), calculated at system start-up. FLIR recommends at least a 512-element LUT (with linear interpolation to 14-bit output resolution).

Compensation for Scene Factors

Section 0 described steps for accurate measurement of a scene with 100% emissivity in close proximity to the camera. Factors such as scene emissivity and unwanted signal from sources other than the scene will influence the measurement accuracy of a real scene. Compensation for these factors is the subject of this section.

Normally, scene materials and surface treatments exhibit emissivity ranging from approximately 10% to nearly 100%. A highly polished mirror falls below 10%, while an oxidized or painted surface can approach 100%. Oil-based paint, regardless of color in the visible spectrum, typically has an emissivity over 90% in the infrared. Human skin exhibits an emissivity of 97% to 98%.

Compensation for emissivity and other scene factors is based on the following model of scene radiation:

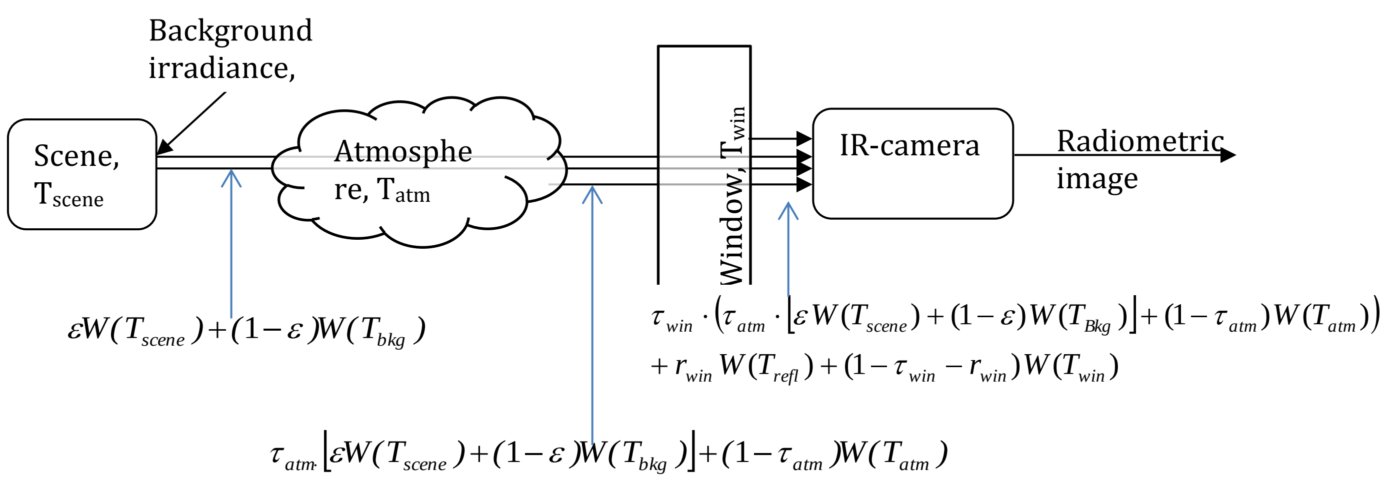


Figure 1: Illustration of the radiation model

The model illustrated in Figure 1 shows the camera signal being a summation of:

1. signal from the scene
2. signal reflected by the background
3. signal emitted by the atmosphere
4. signal reflected by the window
5. signal emitted by the window

Depending upon location in the transmission path, some of these signals are attenuated by emissivity, the atmospheric transmission, and window transmission. Mathematically, this is given by

$$S = \tau_{win} \cdot \left(\tau_{atm} \cdot \left[\varepsilon W(T_{scene}) + (1-\varepsilon) W(T_{Bkg})\right] + (1-\tau_{atm}) W(T_{atm})\right) \\ + r_{win} W(T_{refl}) + (1-\tau_{win} - r_{win}) W(T_{win}),$$

Equation 4

where the various parameters of equation 4 are described in Table 1.

Table 1: Description of the parameters of Equation 4.

Notation	Description
S	Value of the 14-bit digital video, in counts
ε	Emissivity of the scene.
τ_{win}	Transmission coefficient of the window
T_{win}	Window temperature, in Kelvin
r_{win}	Window reflection
T_{refl}	Temperature reflected in the window, in Kelvin
τ_{atm}	Transmission coefficient of the atmosphere between the scene and the camera
T_{atm}	Atmospheric temperature, in Kelvin
T_{bkg}	Background temperature reflected by the scene, in Kelvin
T_{scene}	Scene temperature, in Kelvin
W(T)	Radiated flux (in counts) as function of the temperature of the radiating object

Prior to conversion of the camera signal to scene temperature, the unwanted signal (i.e., from the background, atmosphere, window reflection, and window emission) must first be removed and then the resulting difference scaled to compensate for attenuation factors. Re-arranging Equation 4 to isolate the term $W(T_{scene})$ yields the following:

$$W(T_{scene}) = \frac{S}{(\tau_{win}\cdot\tau_{atm}\cdot\varepsilon)} - \frac{(1-\varepsilon)}{\varepsilon}\cdot W(T_{Bkg}) - \frac{(1-\tau_{atm})}{(\tau_{atm}\cdot\varepsilon)}\cdot W(T_{atm}) - \frac{r_{win}}{(\tau_{win}\cdot\tau_{atm}\cdot\varepsilon)} W(T_{refl}) - \frac{(1-\tau_{win}-r_{win})}{(\tau_{win}\cdot\tau_{atm}\cdot\varepsilon)}\cdot W(T_{win})$$

Equation 5

All of the *W(T)* terms on the right-hand side of Equation 5 can be calculated via Equation 2. After doing so, the right-hand side of Equation 5 is reduced to a single scalar value, which can then be converted back to temperature via Equation 3. An example is shown below.

Example:

- RBFO = (395653, 1428, 1, 156)
- S = 3204 counts. (Note: without compensation for scene factors, this output value from the camera would be converted to a value of 293K using the RBFO parameters substituted into Equation 3.)
- ε = 92%
- τ_{win} = 97%
- T_{win} = 300K
- r_{win} = 3%
- T_{refl} = 315K
- τ_{atm} = 85%
- T_{atm} = 278K
- T_{Bkg} = 278K

Calculations:

$$W(T_{Bkg}) = \frac{R}{\exp(B/T_{Bkg}) - F} + O = \frac{395653}{\exp(1428/278) - 1} + 156 = 2495.0$$

$$W(T_{atm}) = \frac{R}{\exp(B/T_{atm}) - F} + O = \frac{395653}{\exp(1428/278) - 1} + 156 = 2495.0$$

$$W(T_{refl}) = \frac{R}{\exp(B/T_{refl}) - F} + O = \frac{395653}{\exp(1428/315) - 1} + 156 = 4453.4$$

$$W(T_{scene}) = \frac{1}{(0.97 \cdot 0.85 \cdot 0.92)} \cdot 3204 - \frac{0.08}{0.92} \cdot 2495 - \frac{0.15}{(0.85 \cdot 0.92)} \cdot 2495 - \frac{0.03}{(0.97 \cdot 0.85 \cdot 0.92)} 4453 - 0$$

$$W(T_{scene}) = 4223.9 - 217.0 - 478.6 - 176.1 - 0 = 3352$$

$$T_{scene} = \frac{B}{\ln\left(\frac{R}{3352 - O} + F\right)} = 295.9K$$

In this particular example, the difference between the temperature estimate after compensating for scene parameters and the estimate prior to compensation is (295.9K - 293.0K) = 2.9K. Depending upon values for the various parameters, much larger estimation errors are possible if compensation is not performed.

Note that if the RBFO curve is calibrated with the system's protective window in place, as recommended in section 0, then it is not required to correct for window transmission. That is, τ_{win} is considered to be 100% since the calibrated RBFO curve already compensates for window transmission. Furthermore, if the window is located in close proximity to the Lepton such that the dominant source of reflection is the Lepton shutter assembly itself, then it is not essential to compensate for window reflection. Lastly, emission from the window itself can generally be considered negligible since window emissivity is usually very low (i.e., 100% – r_{win} – τ_{win} is typically low) and window temperature not very different from camera temperature. Assuming window effects can be ignored, Equation 5 reduces to the following:

$$W(T_{scene}) = \frac{S}{(\tau_{atm} \cdot \varepsilon)} - \frac{(1-\varepsilon)}{\varepsilon} \cdot W(T_{Bkg}) - \frac{(1-\tau_{atm})}{(\tau_{atm} \cdot \varepsilon)} \cdot W(T_{atm})$$

Equation 6

Radiometric Calibration

The purpose of radiometric calibration is to determine values for the R, B, F, and O parameters used in Equations 2 and 3. These should be generated by obtaining camera output in response to multiple blackbody temperatures and then curve-fitting to find a best fit.

For radiometric calibration, it is recommended to use stable and accurate blackbodies with high emissivity. For accurate calibration, the camera must be in thermal equilibrium. It is recommended to wait at least 5 minutes after start-up (longer if possible) before performing a radiometric calibration and then to image each blackbody in fairly rapid succession to avoid drift effects. It is recommended to perform a single FFC just prior to calibration (see section 0). The FFC should be performed using whatever FFC source will be used in operation. For example, if the integral shutter will be used in normal operation, use it for the FFC just prior to radiometric calibration. Also, if the application includes a protective window located in front of the Lepton, it is recommended to perform the calibration with the protective window in place.

Ideally, the blackbody sources should be located at a distance similar to targets of interest in the application. For example, if the application is used to measure targets that are located in close proximity to the camera, the blackbodies used for calibration should also be located in close proximity. If the application is measuring targets that are more than a meter away, the blackbody sources should also be located at least a meter away. However, the blackbody should subtend a fairly large number of pixels (typically 10x10 at minimum). For the purpose of collecting camera output for curve-fitting, it is recommended to average the output values in a small region of interest (ROI) in the central portion of the image, such as the center 6x6.

Typical values for RBFO = (395653, 1428, 1, 156). Expected ranges are shown below:

- R = [10000, 1000000]
- B = [1200, 1700]
- F = [0.5, 3]
- O = [-16384, 16383]

If F and B are fixed at the typical values shown above, it is possible to calibrate R (the responsivity) and O (the offset) by imaging only 2 blackbodies. However, by using several blackbodies, a more accurate calibration can be obtained since the B parameter, which affects the shape of the curve, can also be best-fit. (The F parameter is generally not varied from a value of 1 except for measurement of very high scene temperatures outside of Lepton's valid range.) Ideally, the selected blackbody temperatures should span the full scene range over which accurate measurement is desired. In other words, to generate an accurate measurement to temperatures in the range 0C to 100C, it is recommended to utilize a 0C and 100C blackbody during calibration. Note: care must be exercised when using a blackbody with a setpoint below the dewpoint because condensation will affect blackbody emissivity and invalidate the calibration.

Figure 2 shows an illustration of the output curve as a function of blackbody temperature. While the principles of nonlinear regression are beyond the scope of this application note, optimum values for the parameters R, B, and O can be determined by fitting to the measured output. These parameters are then used in Equations 2 and 3 to convert between camera output and scene temperature.

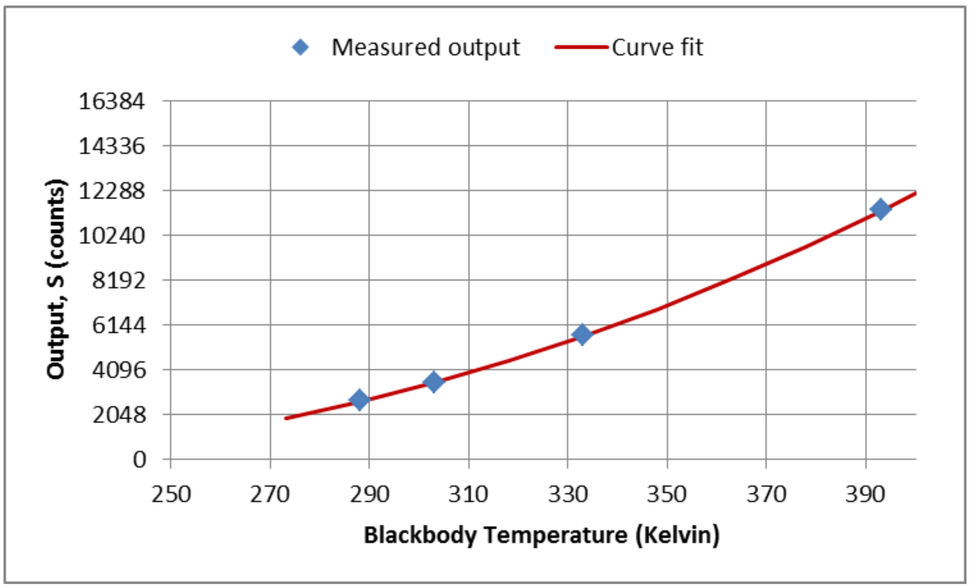


Figure 2: Example calibration curve

Flat-field Correction (FFC)

Flat-field correction (FFC) is a process that allows both image uniformity and radiometric accuracy to be improved during runtime by letting the camera update internal offset terms while imaging a uniform scene of known temperature. This uniform scene is referred to herein as the FFC source. The FFC process takes under 1 second to complete. Some Lepton configurations include an integral shutter assembly that can be used as the FFC source. (When the shutter is closed, it completely subtends the field of view.) However, even configurations without an integral shutter assembly can utilize FFC to improve radiometric accuracy, provided the temperature of the external FFC source is measured and communicated to the camera.

Configurations with an integral shutter provide three valid FFC modes, and the optimum mode is application dependent. (For example, in some applications, it might not be desirable for the camera to automatically initiate FFC since the video signal is temporarily "frozen" during the FFC process.)

1. Automatic: The camera automatically initiates FFC using the integral shutter assembly on a periodic basis (i.e., when the elapsed time since the last FFC exceeds a user-specified value or when the camera temperature has changed by a user-specified amount since the last FFC).
2. Manual: The camera performs FFC using the integral shutter assembly only when user-commanded.
3. External: The camera performs FFC on an external source only when user-commanded. Note that this is the *only* valid FFC mode for Lepton configurations without an integral shutter assembly.

There are two available commands for a user-initiated FFC, the *OEM FFC Normalization* command and the *RAD FFC Normalization* command. Only the *RAD FFC Normalization* command should be used when radiometric mode is enabled because it is that command which causes the camera to properly adjust its radiometric offsets. (The *OEM FFC Normalization* command is intended for non-radiometric mode.) The adjustment causes the output value to be correct for the particular temperature of the FFC target, referred to as Tshutter. (In the case of external FFC, the FFC source is not a shutter, but the source temperature is still referred to as Tshutter for simplicity.)

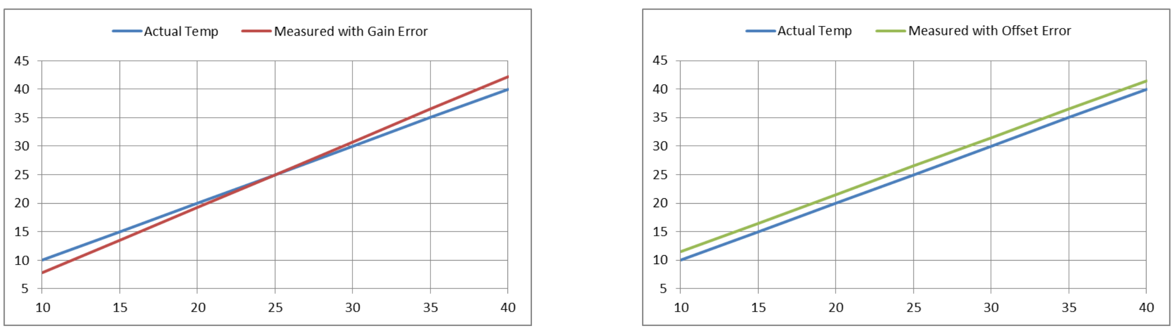
There are two possible modes for determining Tshutter. In what is referred to as "Cal Tshutter mode", the camera automatically estimates Tshutter at the time of FFC based on its own internal temperature sensors. In “User Tshutter mode”, the user specifies the temperature of the shutter prior to FFC using the *RAD Tshutter Temperature* command. “User Tshutter mode” is more appropriate whenever the user has a better estimate of Tshutter than the camera. Two such examples include the following:

- When an external FFC is commanded, in which case the Lepton camera has no means of directly knowing the temperature of the FFC source. Using its internal temperature sensors to estimate the temperature of an external source is clearly not appropriate in this scenario.
- If the Lepton shutter assembly is instrumented with a calibrated thermocouple or other measurement device that is read by an external host, a more accurate estimate of the shutter is possible. This is because Lepton’s internal temperature sensors are not located directly on the shutter assembly, and therefore the estimate when in “Cal Tshutter mode” is subject to slight error. For best radiometric accuracy, use of an external thermocouple is recommended. Figure 3 shows an example mounting of a thermocouple onto the shutter assembly.

Figure 3: Example of a thermocouple mounted directly to the Lepton shutter assembly

Sources of Error

Fundamentally, there are two distinct types of temperature-measurement error: gain error and offset error. For gain error, the magnitude is small when the scene temperature is similar to the camera temperature, but it grows increasingly larger with temperature difference as illustrated in Figure 4a. In contrast, an offset error has the same magnitude regardless of the scene temperature, as illustrated in Figure 4b. Understanding the type of measurement error, gain or offset, is an important first step in mitigation efforts since some of the root causes of error are primarily related to gain while other are primarily related to offset.



(a) Gain error (b) Offset error

Figure 4: Illustration of gain and offset error

One of the most likely sources of offset error is unwanted signal from the camera's own housing when the camera is not in thermal equilibrium. This unwanted signal, called out-of-field irradiance, is a source of both image non-uniformity and radiometric offset error. The most ideal condition for temperature measurement is when the camera has been powered on and operated in a stable temperature long enough to have achieved steady-state operation such that there is no out-of-field irradiance. Lepton is factory-calibrated to produce a stable output even as its own temperature changes, but when exposed to rapid changes, there is a greater likelihood that the housing and sensor fall out of equilibrium. At start-up in particular, the Lepton camera heats up rapidly in the first minute of operation and is particularly prone to out-of-field irradiance. Frequent FFC will mitigate the problem, but performing FFC too frequently with Lepton's integral shutter is also problematic. Each FFC operation dissipates approximately 700 mJ, which further exacerbates the problem of rapid temperature change and loss of equilibrium. The best case scenario is to avoid temperature measurement in the first minute after turn-on (or after other sudden, rapid temperature changes) and to avoid performing FFC with the internal shutter more frequently than once per minute.

Another potential source of offset error is a bad estimate of Tshutter during FFC. As described in Section 0, Lepton performs its own estimate of the shutter temperature when operating in “Cal Tshutter Mode”. The estimate uses a temperature sensor located internal to the camera housing, which tracks the shutter temperature fairly well during steady-state conditions. However, in thermally-dynamic scenarios and/or during periods of frequent operation of the shutter, the estimate from the internal sensor is prone to error. For best performance, it is recommended to install a calibrated thermocouple directly to the shutter cover plate and provide the Lepton with its estimate of Tshutter prior to each FFC.

The primary sources of gain error are poor calibration and/or a poor estimate of attenuation sources, such as emissivity. A less obvious source of gain error is sensor saturation (i.e., attempting to image a source hotter than the 400K upper scene range of the device).

Frequently-Asked Questions

Radiometric Physics

Q. How does the distance between the target and the camera affect the temperature measurement?
A. If atmospheric attenuation is properly compensated, distance does not significantly affect the measurement value, provided the target is not smaller than a pixel (or the aggregate spot size if multiple pixels are averaged). Temperature measurements are not valid for sub-pixel targets because irradiance decreases with target distance in such cases. Note that optical blur can also influence the measurement of targets that are on the order of a pixel; for best-case performance, the target should subtend several pixels (>10).

It should be noted that placing a source very close to the camera can also cause slight measurement differences as the result of stray-light effects. That is why it is preferred to perform radiometric calibration with sources located approximately as close to the camera as targets of interest rather than to use flood sources located just in front of the camera.

Q. How do I know the emissivity of the object I am attempting to measure?
A. There are multiple published sources which list emissivity in the LWIR waveband for common materials, including online lists. It is also possible to determine the emissivity of an object empirically by knowing its temperature (e.g., with a contact thermometer) and finding the emissivity value that causes the temperature measurement with the Lepton camera to match. Note that measuring a highly-reflective source is prone to significant measurement error due to background irradiance, and a common thermographer's trick is to cover a portion of the surface with a piece of electrical tape or some other material with high emissivity.

Q. How do I know the atmospheric attenuation?
A. Estimating atmospheric attenuation is a complicated subject well outside the scope of this application note. However, it is worth noting that attenuation is typically negligible

for close-range measurements (e.g., < 10 meters) except in cases of extreme humidity. For long distances, it is possible to measure transmission empirically by locating a target down range with known temperature and emissivity (similar in principle to the method described in the previous question for empirical estimation of emissivity).

Q. In my application, a protective window sits in front of the Lepton. Will this window affect my temperature measurements?
A. As discussed in section 0, it is recommended to perform radiometric calibration with the window in place, in which case its spectral transmission will be included in the RFBO curve. If a window is installed after calibration, effects of window transmission should be compensated as described in Section 0.

Controls-Related Questions

Note: For syntax information regarding the various commands, see the latest release of the Lepton Software IDD – OEM (FLIR doc# 110-0144-04).

Q. How is radiometric mode enabled?
A. Using the *RAD Radiometry Control* command.

Q. What's the difference between Radiometry Disabled mode and Radiometry Enabled mode?
A. The radiometric modes affect the transfer function between incident flux and 14-bit pixel output. With radiometry disabled, the output of the camera for a given scene varies over as a function of camera temperature. Furthermore, the responsivity (i.e., the change in output value for a change in input, δout / δin) varies as well, decreasing with increasing camera temperature. This condition is illustrated hypothetically in Figure 5. (Note that the figure is for illustration purposes and not perfectly representative of camera output.) With radiometry enabled, Lepton performs internal adjustments to the signal level such that in principle the output is independent of the camera's own temperature. The resulting output for three different scene

temperatures is illustrated hypothetically in Figure 6. Notice in Figure 6 that the output is only a function of scene temperature, not camera temperature. Also notice that responsivity is also independent of camera temperature; that is, the difference in output between two different scene temperatures is a constant. (Again, the figure is for illustration purposes only and not perfectly representative. In practice, there will be slight output variation as camera temperature changes, particularly when the temperature change is rapid.)

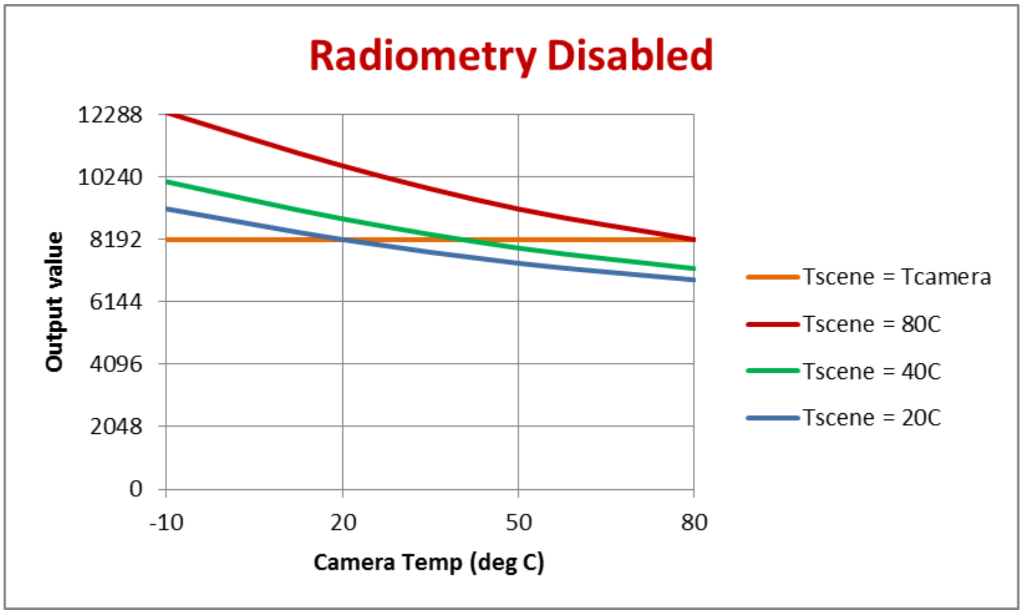


Figure 5: Hypothetical illustration of camera output vs. camera temperature in radiometry-disabled mode

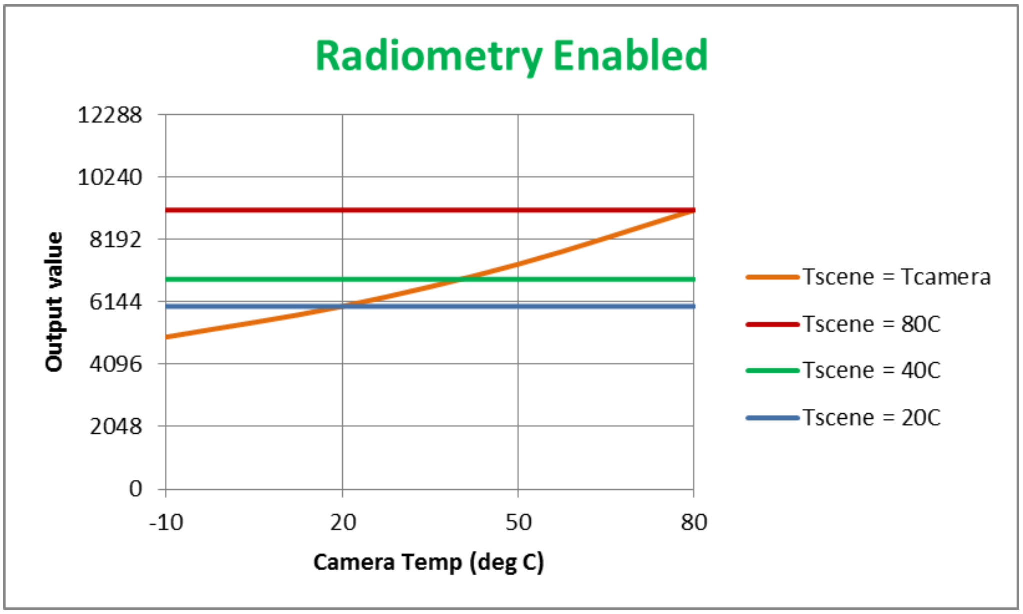


Figure 6: Hypothetical illustration of camera output vs. camera temperature in radiometry-enabled mode

Q. There are two available commands for initiating an FFC operation, *OEM FFC Normalization* and *RAD FFC Normalization*? What is the difference between the two and which is more appropriate?

A. The *OEM FFC Normalization* command is more appropriate when radiometric mode is disabled. It always forces the mean output of the array to a given value (nominally 8192) when viewing the FFC source. The *RAD FFC Normalization* command is more appropriate when radiometric mode is enabled – it forces the output of the array to a value that is radiometrically correct.

Q. What are the Tshutter modes?

A. During each FFC operation, Lepton uses the temperature of the FFC source to offset-correct its radiometry calculations. The Tshutter mode determines the source of the shutter-temperature estimate. In the current Lepton release, there are two valid Tshutter modes: Cal and User. In Cal mode, Lepton utilizes internal temperature sensors to estimate the shutter temperature at the time of FFC. In User mode, the host specifies the temperature of the shutter via the *RAD Tshutter Temperature* command, and Lepton uses the last specified value at FFC.

Q. Which Tshutter mode is more appropriate?

A. The correct answer is application-dependent. Whenever the customer's external host has a better estimate of the shutter temperature than the Lepton, the User mode is more appropriate. Two such examples include the following:

- FFC is performed using an external FFC source (i.e., the Lepton has no integral shutter or the FFC mode is set to "external" such that the shutter is not closed during FFC). The external host should provide the temperature of the external FFC source via the *RAD Tshutter Temperature* command prior to commanding FFC with the *RAD FFC Normalization* command.
- The Lepton shutter assembly is instrumented with a calibrated thermocouple or other measurement device that is read by the external host. Generally speaking, a thermocouple located directly on the shutter assembly will provide a better temperature estimate than those sensors internal to the Lepton (which are not currently located on the Lepton shutter assembly). Note: in a future release of Lepton, Lepton will employ an internal temperature sensor in intimate contact with the shutter assembly.

Q. If I am operating the Lepton in "User Tshutter Mode", how often do I need to send the Tshutter value?

A. The only time Lepton uses the Tshutter value is during FFC. Therefore, it is sufficient to send the Tshutter value just prior to FFC.

Q. Do I need to use the RAD RBFO External Parameters command?

A. No. This command is intended for a later release of Lepton.

Calibration

Q. How many blackbodies should I use in calibration?
A. At minimum, two blackbodies will allow calibration of the R and O parameters. However, it is recommended to utilize at least three blackbodies (more if possible) such that R, B and O can be curve-fit. It is not recommended to curve-fit the F parameter; a value of 1 should always be used.

Q. What temperatures should I select for my calibration blackbodies?
A. Best performance is achieved when the blackbodies span the full scene range of interest. For example, to obtain good performance from 20C to 110C, calibration temperatures of 20C, 50C, 80C, and 110C are appropriate. If best accuracy is required within a small temperature span, for example, 20C to 30C, it is recommended to include a 20C and 30C blackbody in the calibration set.

Q. Should I flood the entire field of view with the blackbody?
A. It is not recommended to flood the entire field of view. Ideally the blackbody sources should be similar in size (in the Lepton image) to the size of typical targets of interest in the application but no less than an area of 10x10 pixels.

Q. Should I perform FFC before calibration? Should I perform FFC on each blackbody?
A. It is recommended to perform FFC just before starting the calibration in the same manner that will be used in the application. FFC should not be performed in the middle of the calibration process.

Q. Can I use a single blackbody head and change its temperature multiple times during the calibration process?
A. In principle, yes. However, it is undesirable for the camera temperature to drift during the calibration process (for example, as the result of radiative heating from the blackbody itself). Therefore, it is recommended to collect data from each scene temperature as rapidly as possible, and using multiple blackbody sources will help accelerate the process.

Q. Should I include my protective window during the calibration process?

A. Best results are obtained by including the window in the calibration process since it has its own spectral signature that will affect the shape of the RBFO curve. If the window is included in calibration, Equation 6 should be used to compensate for scene factors rather than Equation 5, as described in Section 0.

If you have questions that are not covered in this manual, or need service, contact FLIR Commercial Systems Customer Support at 805.964.9797 for additional information prior to returning a camera.

This documentation is subject to change without notice.

This equipment must be disposed of as electronic waste.
Contact your nearest FLIR Commercial Systems, Inc. representative for instructions on how to return the product to FLIR for proper disposal.

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