A6600/A6650

User's Manual

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1 Revision History

Version	Date	Initials	Changes
1	03/10/2015	RM	Initial Release

2 Introduction

2.1 Camera System Components

The A6600 infrared camera and its accessories are delivered in a box which typically contains the items below. There may also be additional items that you have ordered such as lenses, software, CDs, etc.

Description	FLIR Part Number
A66xx Camera	29360-2xx
Power supply, 24V, 4A	24123-000
AC line cord	24124-000
Gigabit Ethernet Cat-6 cable, 2m length	23700-000
Bayonet mount plug	23901-000
BNC cable	26393-000
CameraTools Cd	N/A
AUX connector breakout cable [A6650 only]	29402-500
Laboratory calibration plate	261-0005-00
Water-resistant transit case	24043-000
Documentation CD	N/A

2.2 System Overview

The A6600 infrared camera system has been developed by FLIR Advanced Thermal Solutions (ATS) to meet the needs of the Automation user. The camera makes use of FLIR's advanced ISC0403 4-channel readout integrated circuit (ROIC), mated to an Indium Antimonide (InSb) detector to cover the midwave infrared band. The A6600 camera utilizes a large format, 640 x 512 array with 15µm pixel pitch.

The A6600 is a stand-alone imaging camera that interfaces to host PC using Gigabit Ethernet. An SDK is available, which makes it possible for the system designer to write their own camera controller and acquire image data with their own custom application.

2.3 Key features of the A6600/A6650 cameras

Fully GEV/GenICam compliant

The image stream protocol is GigE Vision 2.0 compliant and the camera is <u>fully</u> controllable by GenICam.

Improved Linearity to Zero Well-Fill

Typical direct injection ROIC designs exhibit a non-linear response when the signal drops below 10% of well-fill. The ISC0403 ROIC provides a linear response even at very low signal levels. This results in an increased linear dynamic range, much better NUC performance at low signal levels and makes it easier to perform a user calibration of the camera.

14-Bit Digital Image Data

The A6600 camera system is built around high performance 14-bit A/D converters, preserving the full dynamic range of the FPA.

Windowing Capability

Higher frame rates are available by windowing down at the Focal Plane Array (FPA) level. The A6600 has three available window sizes with a max frame rate of 480Hz. The A6650 has flexible window sizes with frame rates up to 4kHz.

Presets

Up to four presets and their associated parameters such as integration time, frame rate, and window size, are available for instant selection with a single command.

Superframing [A6650 only]

Up to four presets can be cycled continuously. This can be used in conjunction with the Dynamic Range Extension (DRX) algorithm to provide a single movie with increased dynamic range.

Independently Adjustable Frame Rates

Frame rate is user selectable from 0.0015 Hz up to the maximum allowed for the selected window size.

External Sync

The A6600 camera provides a SYNC input that can be used to control the camera frame rate using an external LVCMOS input (can handle 5.5V Max).

External Trigger [A6650 only]

An external trigger input can be used to signal ResearchIR to start recording or to precisely start the image stream relative to an external event.

Multiple Video Outputs

The A6600 camera features multiple independent and simultaneous video:

- Digital – Gigabit Ethernet
- Analog – Composite video (NTSC or PAL)

Analog Video Color Palettes

The A6600 camera supports a selection of standard and user-defined color palettes for the analog video output.

Digital Detail Enhancement (DDE)

DDE is an analog video AGC mode that provides a significant improvement to scene detail and contrast.

On-Camera NUCs with Auto Update

NUCs can be stored in camera memory and can be applied independently to the digital and analog video outputs. The camera can be configured to automatically update the NUC using the internal flag based on a change of an internal temperature sensor and/or a timer.

Standard Lens Interface

The A6600 camera uses the same bayonet-mount as other SCx000 series cameras. However, even though the mount is the same, due to differences in the opto-mechanical layout, lenses for the SC6000/4000 are not an optimal solution for the A6600. The SC6000 lenses will provide fairly good imagery but some vignetting in the corners may be visible. For best performance the user should use lenses designed for the A6600. Lenses for the SC8000 will not work on the A6600.

3 Warnings and Cautions

For best results and user safety, the following warnings and precautions should be followed when handling and operating the camera.

⚠ Warnings and Cautions:

- **Do not open the camera body for any reason. Disassembly of the camera (including removal of the cover) can cause permanent damage and will void the warranty.**
- **Great care should be exercised with your camera optics. Refer to Chapter 7 for lens cleaning.**
- **Operating the camera outside of the specified input voltage range or the specified operating temperature range can cause permanent damage.**
- **The camera is not completely sealed. Avoid exposure to dust and moisture and replace the lens cap when not in use.**
- **Do not image extremely high intensity radiation sources, such as the sun, lasers, arc welders, etc.**
- **The camera is a precision optical instrument and should not be exposed to excessive shock and/or vibration. Refer to the Chapter 6 for detailed environmental requirements.**
- **The camera contains static-sensitive electronics and should be handled appropriately.**

4 Installation

4.1 Basic Connections

All connections to the A6600/A6650 are located on the Back Panel.

Item	Name	Description
1	Power Switch	LED will light when power is ON
2	Ready Light	LED will turn on when camera is booted
3	Cold LED	LED will light when FPA temp is <80K
4	Gigabit Ethernet (RJ45)	Connect to a PC for digital IR image data
5	AUX Connector	A675xsc only. (See Section 6.1.3.4 for details)
6	DC Power Input	24VDC
7	Sync Input	External Frame Sync
8	Video Out	NTSC or PAL, selectable in camera controller

4.1.1 Power

Plug in the AC power supply to a standard 120V outlet. Connect the DC power cable between the power supply and the power connector located on the rear panel of the A6600 camera.   Turn on the imaging head by pressing the power button on the rear panel. The green power LED will illuminate to indicate that the unit is ON.

4.1.2 Analog Video

The camera will automatically boot up into the last saved state. The boot process takes about 30 seconds. To see the Composite video on a monitor, connect the provided BNC cable from the VIDEO port to your monitor. If you are powering up the camera for the first time, the camera should produce a 640x480 image with Non-Unifority Correction (NUC), bad pixel replacement enabled.

4.1.3 GigE Digital Video

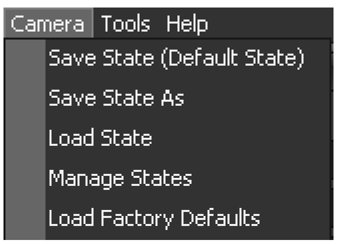
If you have a PC data system running ResearchIR (or your own custom application based on the BHP SDK or Genicam) you can view the 14-bit digital video over Gigabit Ethernet.

The A6600 has a Gigabit Ethernet interface that is GigE Vision (GEV) and GenICam compliant Use a regular CAT5e or CAT6 Ethernet patch cable. If a crossover cable is used, the camera interface will automatically detect and configure itself to work with this kind of cable.

5 Camera Controller

5.1 Menu Bar

The menu bar is the same for both Basic and Advanced User Modes.

	Save State (name)	Saves the camera state to the current (name). This state will be reloaded at power up. Stored in flash memory.
	Save State As	Saves the current camera state to a name chosen by the user. State names other than (name) my be loaded manually. Stored in flash memory
	Load State	Load a state from flash memory.
	Manage States	Rename or delete states from camera memory.
	Load Factory Defaults	Loads factory defaults for all camera Settings and NUCs. The factory defaults cannot be modified by the user.

NOTE: Camera states contain information about all configurable camera parameters. They do not contain the NUC data, but contain the filenames of the currently loaded NUCs. These NUCs will be reloaded with the state, however, if the NUCs are changed, deleted, or renamed, the state may not be able to load the NUCs.

5.1.1 Tools Menu

	Set Camera Time to PC Time	Sets the camera RTC clock to the time from the PC clock.
	Advanced…	Allows user to manually set the IRIG and RTC clocks in the camera. See Section 4.2.2.1

NOTE: The A6600 has two internal clocks: a Real Time Clock (RTC) and a timestamp clock. The RTC is a low resolution clock used to keep system time. The RTC has a battery backup and will retain time while the camera is off. The timestamp clock is a high resolution clock (1us). This clock does not have a battery backup but at power up the timestamp clock is initialized to the current RTC time and will free-wheel until the camera is power cycled.

Advanced Time Controls

This dialog is accessed using the Tools>>Set Time>>Advanced menu options. This allows the user to directly set the cameras system time. The Get button will pull time from the PC clock. The Set button will set the camera RTC clock using the manually entered time.

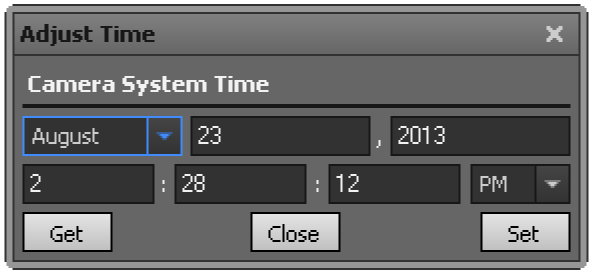
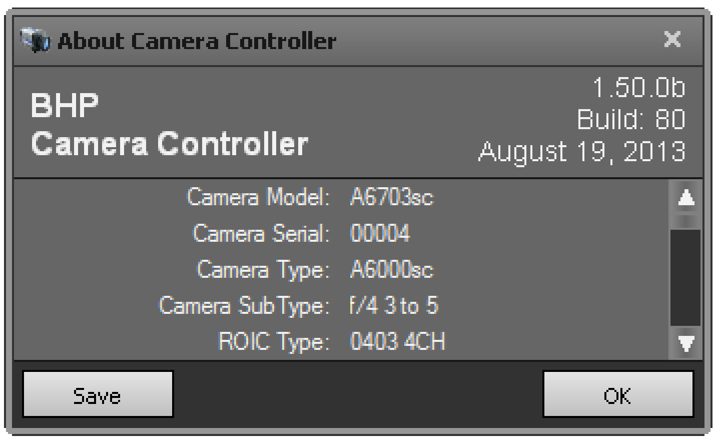


Figure 4-1 Advanced Time Controls

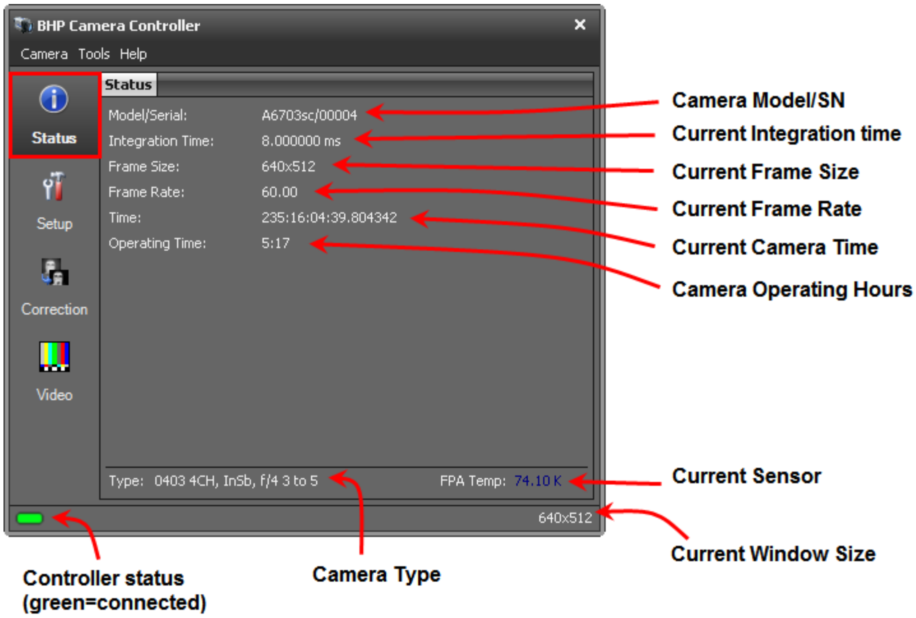
5.1.2 Help Menu

The "About" menu item shows a dialog indicating the current controller version number. If the controller is connected to a camera a list will be displayed that shows all versions of software and firmware in the camera. The "Save" button allows the user to create a text file with this version information.



5.1.3 Status Page

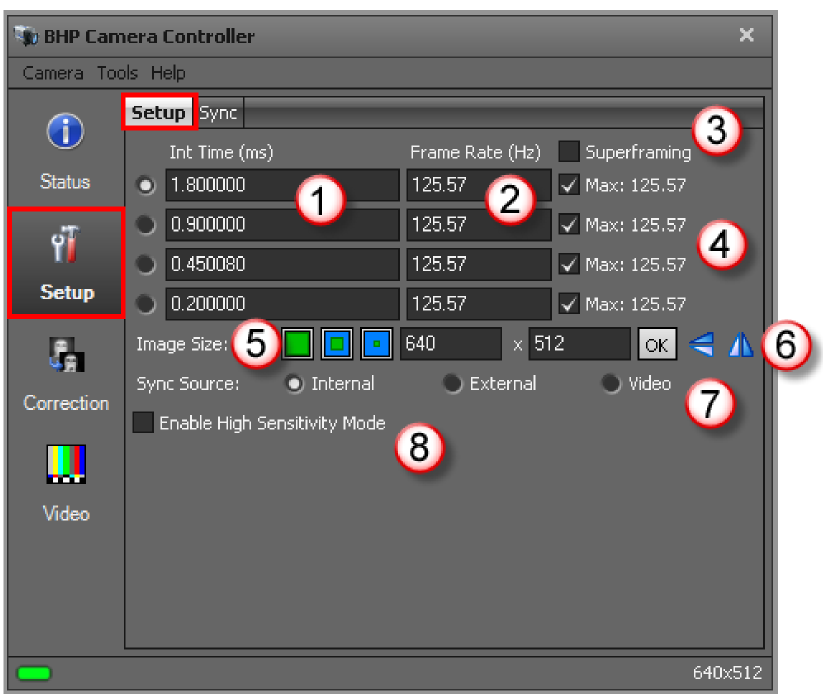
The Status Page gives general information about the camera state including camera type, camera time, integration time, frame size, and frame rate.



5.1.4 Setup Page

The Setup page allows the user to set integration time, frame rate, frame size, and Sync source.

5.1.4.1 Setup Tab

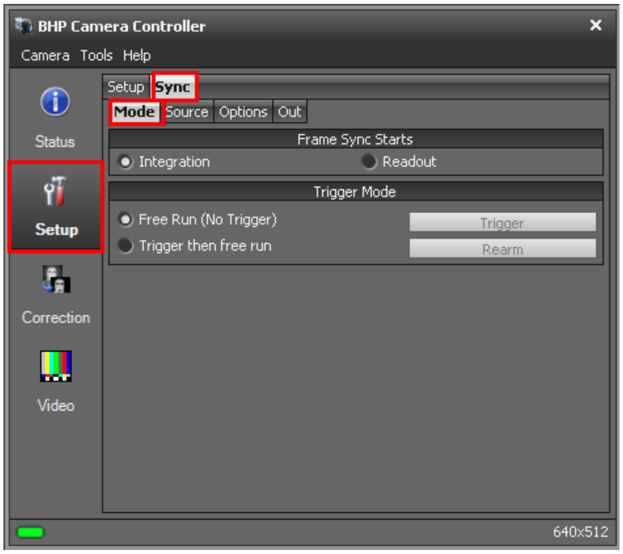


Item	Name	Description
1	Integration Time	No factory calibration: Enter desired integration time in milliseconds. With factory calibration: The box will have a dropdown list with the available ranges. To manually enter integration time scroll to bottom of list and select “no factory calibration”.
2	Frame Rate	Enter the desired frame rate in Hz.
3	Superframing	**[A6650 only].** When this is enabled the user can then select the presets to include and set the burst rate.
4	Max Frame Rate	This indicates the max possible frame rate based on the current window size and integration time. Checking the box will automatically keep the camera at max frame rate as these parameters change.
5	Image size	A6600: This control will be simply a dropdown list with the three window size options available (Full, ½, ¼). A6650: There are buttons to select Full, ½, ¼ windows as well as boxes to enter other sizes. Click “OK” to set a size. The box will turn red if the size is not valid.
6	Image Flipping	The  icons control horizontal and vertical image flipping. With these controls, the flipping is done in the camera so both the digital and analog video are affected.
7	Sync Source	Select internal, external, or video. Internal: The frame sync is generated internally to run at the frequency set by the user External: The frame sync is generated externally through the Sync In connect on the camera rear chassis. Video: The FPA frame sync is generated from the internal video encoder , locking the digital and analog clocks together
8	High Sensitivity Mode (HSM)	HSM is a FLIR-patented algorithm first introduced in the Gas FindIR cameras that allows the user to see small temperature changes in the scene.

5.1.4.2Sync Tab [A6650 only]

The sync tab allows the user to control function for Syncs, and triggers. All of these sync features apply only to the A6650.

5.1.4.2.1   Sync Mode



5.1.4.2.1.1 Frame Sync Starts

The A6650 makes use of frame syncs and triggers to control the generation of image data. Frame syncs control the start of individual frames whereas triggers start sequences of frames.

The generation of a frame consists of two phases: *integration* and *data readout*. Depending on the timing between these two events, you can have two basic integration modes: Integrate Then Read (ITR), and Integrate While Read (IWR). In ITR, integration and data readout occur sequentially. The complete frame time is the combined total of the integration time plus readout time. In IWR, the integration phase of the current frame occurs during the readout phase of the *previous* frame. In other words, ITR and IWR terms refer to whether or not the camera will overlap the data readout and integration periods. In ITR, the data is not overlapped which means lower frame rates but provides a less noisy image. IWR can achieve much faster frame rates with a slight increase in noise. The A6650 does not require the user to explicitly choose whether to operate in ITR or IWR modes. The camera will automatically select the integration mode based on the integration time, frame rate, and frame sync mode.

The A6650 supports two Frame Sync Modes: Frame Sync Starts Integration (FSSI), and Frame Sync Starts Readout (FSSR). FSSI and FSSR determine which phase of the frame generation process (integration or data readout) is synchronized to the frame sync. FSSI starts the integration period when a frame sync occurs (i.e. “take a picture now”). The camera automatically calculates when to start data readout. FSSR starts the data readout (for the previous frame) when a frame sync occurs (i.e. “give me data now”). The camera automatically calculates when to start integration for the current frame. In FSSI mode, the camera could be in either ITR or IWR mode. In FSSR mode, the camera is always in IWR mode.

5.1.4.2.1.1.1 Frame Sync Starts Integration (FSSI)

Upon frame sync, the camera immediately integrates followed by data read out. Based on integration time, frame size, and frame rate, the camera will automatically choose ITR or IWR mode.

NOTE: When using an external frame sync and superframing, the external frame sync should be set to comply with ITR frame rate limits. If the external sync rate is too fast, the camera will ignore syncs that come before the camera is ready

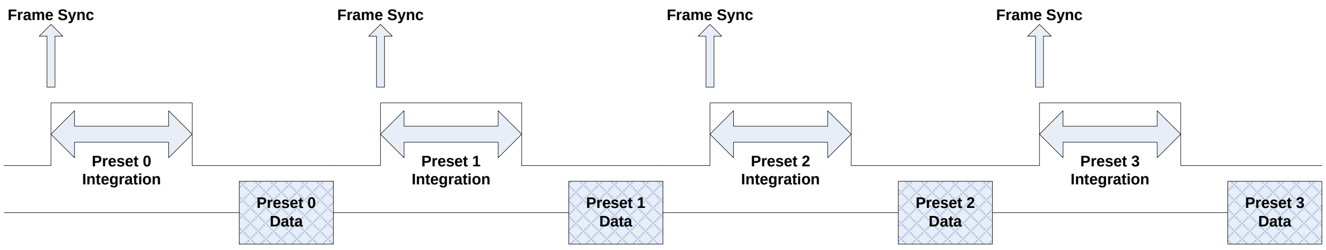


Figure 4-2: Frame Sync Starts Integration, ITR

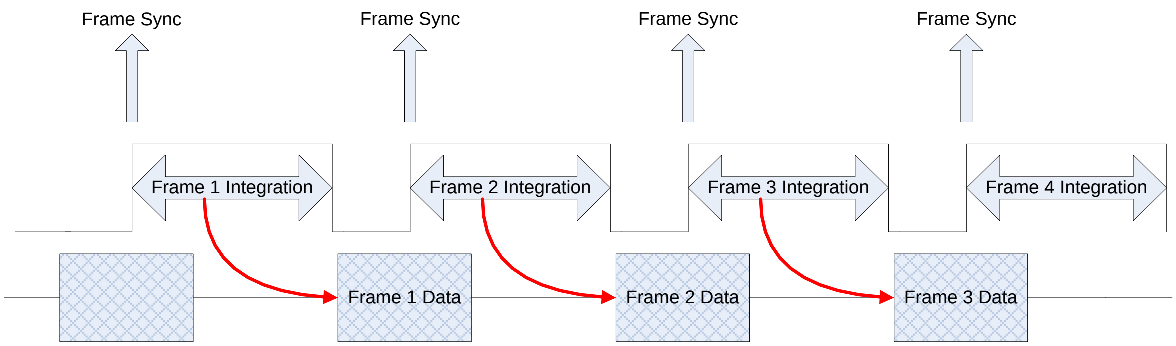


Figure 4-3: Frame Sync Starts Integration, IWR

5.1.4.2.1.1.2 Frame Sync Starts Readout (FSSR)

Upon frame sync, the camera immediately transmits the data from the previous frame. The integration period is then placed to meet ROIC requirements. This mode always operates in IWR mode. This mode can be used with either internal or external frame sync at full frame rates.

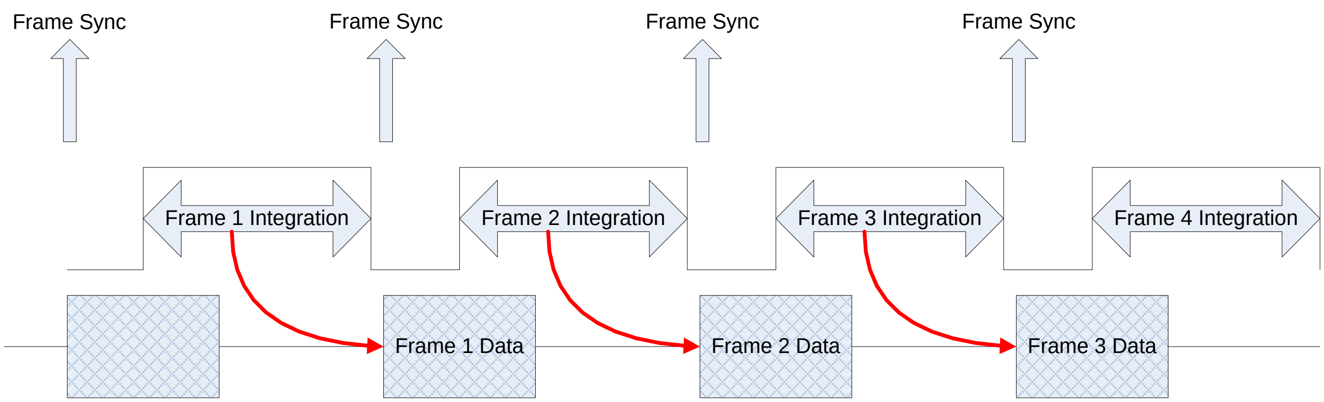


Figure 4-4: Frame Sync Starts Readout

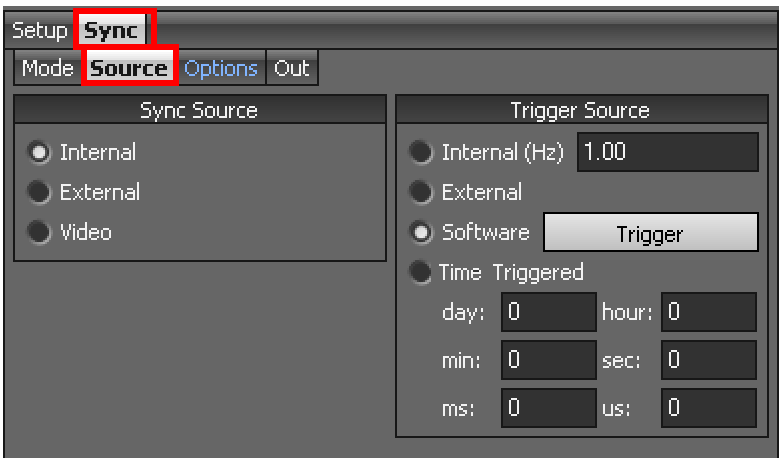
5.1.4.2.1.2 Trigger Mode

When the camera is placed in a triggered mode, the image stream will stop until the trigger is received.

Trigger Modes	
Free Run (No Trigger)	In free run the camera cycles through frames/sequences continuously.
Trigger then free run	Upon receiving a trigger (external or software) the camera will start to generate sequences continuously.

5.1.4.2.2 Sync Source

The Source options page allows the user to select the source for Syncs and Triggers.

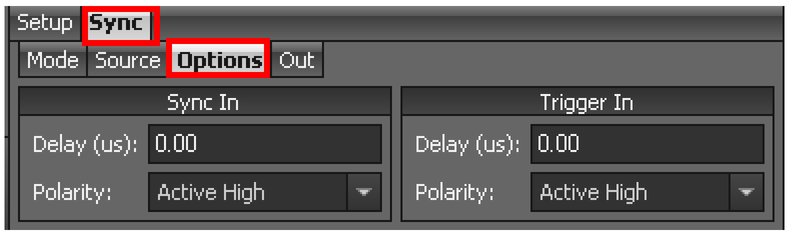


Sync Sources	
Internal	The frame sync is generated internally to run at the frequency set by the user
External	The frame sync is generated externally through the Sync In connect on the camera rear chassis.
Video	The frame sync is generated from the internal video encoder, locking the analog video and FPA clocks together.
Trigger Sources	
Internal	The trigger is generated internally to run at the frequency set by the user (Hz).
External	The trigger is generated externally through the Trigger In

	connector on the camera rear chassis. (3.3V LVCMOS)
Software	The trigger is generated via a software button (Trigger button)
Time Triggered	Camera generates an internal trigger when the internal timestamp clock reaches a specified time.

5.1.4.2.3 Sync Options

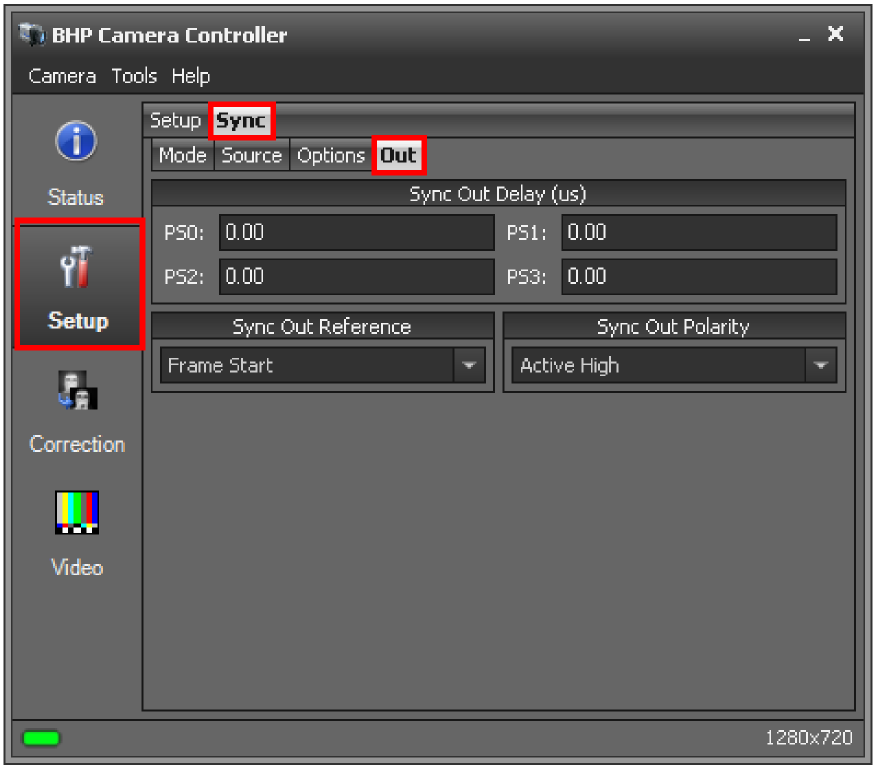
The Sync Options page allows the user to set delays and polarities for the Sync and Trigger In.



Sync In	
Delay	Allows for the user to set a delay (µsec) for the external sync. See timing diagrams below.
Polarity	The sync is edge triggered. Allows for the camera to use the rising or falling edge.
Trigger In	
Delay	Allows for the user to set a delay (µsec) for the external trigger. See timing diagrams below.
Polarity	Trigger is edge triggered. Allows for the camera to use the rising or falling edge.

5.1.4.2.4 Sync Out

The Sync Out options allow the user to set a delay for the sync out pulse as well as the sync delay reference and polarity. The Sync Out signal always has a jitter of ±1 clock (160nsec).



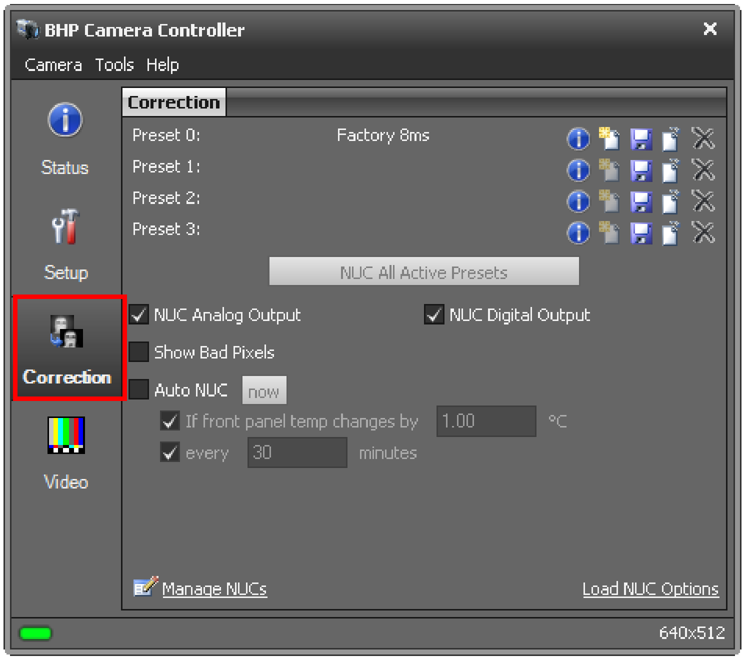
Sync Out Options	
Sync Out Delay	Allows for the user to set a delay for the sync out on a preset basis.
Sync Out Source	Allows for the sync out to be referenced to the start of frame or start of integration.
Sync Out Polarity	Allows for the sync out to be active high or low.

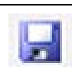
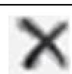
5.1.5 Correction Page

The Correction Tab contains all the controls needed to manage the on-camera NUCs. On-camera NUCs are stored in two types of memory:

RAM memory. This type of memory is used to store NUCs that will be applied to live image data. There is enough RAM memory for one NUC to be loaded for each Preset. This memory is volatile and is lost when then camera is turned off. If a NUC was loaded into RAM, the camera will reload that NUC from flash automatically when the camera is turned on if a Save State was performed.

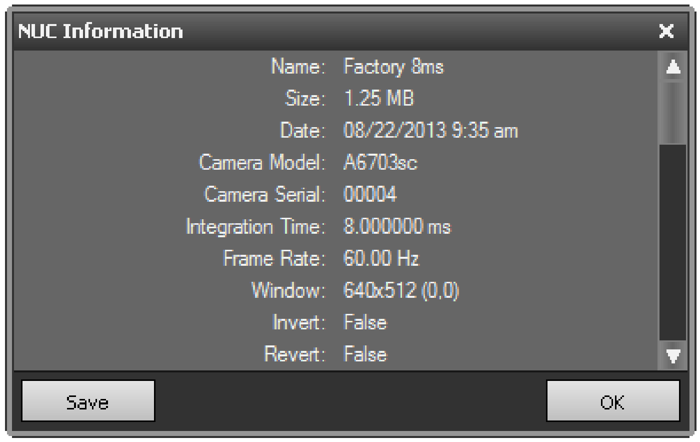
Flash Memory. This type of memory is used as nonvolatile NUC storage. There is about 2GB of flash memory available for storing NUCs. This is enough space to store hundreds of full frame NUCs.



NUC Controls	
	NUC Info. Displays camera parameters and statistics related to the selected NUC
	Perform NUC. Starts the NUC Wizard.
	Updates the current NUC to flash memory
	Load a NUC from flash to RAM memory.
	Unload NUC from RAM memory. No on-camera NUC will be applied to the data.
NUC Analog Output	Apply NUC to Analog video data
NUC Digital Output	Apply NUC to Digital output (GigE, CameraLink)
Show Bad Pixels	Displays all pixels marked as “bad” as white dots on both the analog and digital outputs.
Auto NUC	When enabled, the camera will automatically drop the internal flag and perform a NUC Offset Update when selected criteria are met. The NUC update can be triggered on demand, by a change in the internal temperature sensor or by a timer
Manage NUCs	Displays a list of NUCs stored in flash memory. User can delete NUCs from flash memory as well as upload/download NUCs (.NPK files) from the host PC.
Load NUC Options	Displays options for loading NUCs.

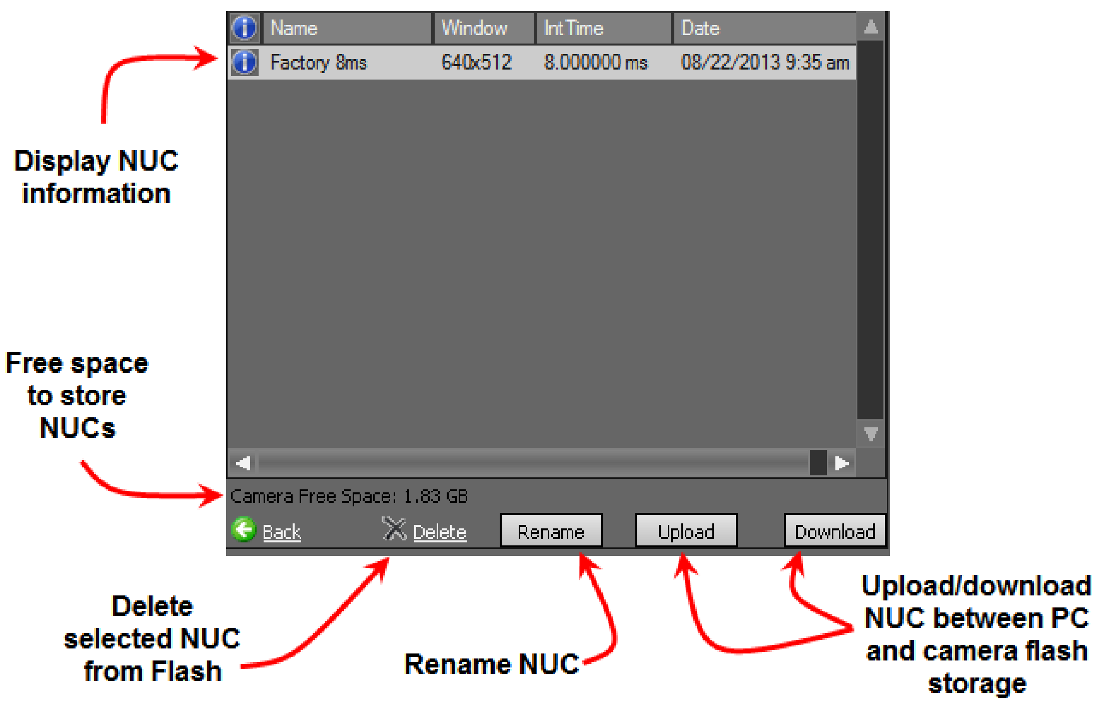
NUC Information

The button displays a list of camera parameters that are saved as part of the NUC as well as bad pixel statistics. Note that there is a scroll bar that can be used to see the whole list. The Save button allows the user to dump this list to a text file.



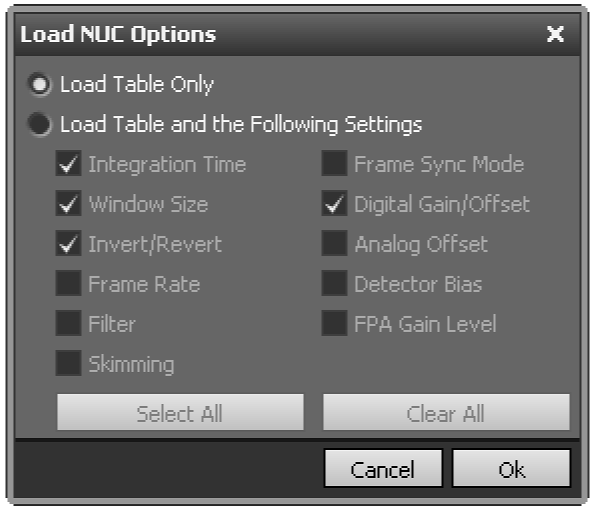
Manage NUCs

This dialog box allows the user to manage NUCs stored in non-volatile flash memory. Changes here will persists through a camera power cycle. For example, if you rename a NUC here and do not update the NUC loaded into RAM and the camera state, the camera will not be able to reload the NUC after a power cycle.



Load NUC Options

Typically, all of the camera configuration parameters are derived from the current Camera State. When the camera is powered up, it loads the last saved camera state. The names of the NUCs are stored as part of the state. Normally the NUC is performed with the settings that are eventually going to be part of the state. If a NUC is loaded that has a setting that differs from the camera state, the state will override the NUC. If the user wants the NUC setting to override the state then “Load NUC Options” can be set.



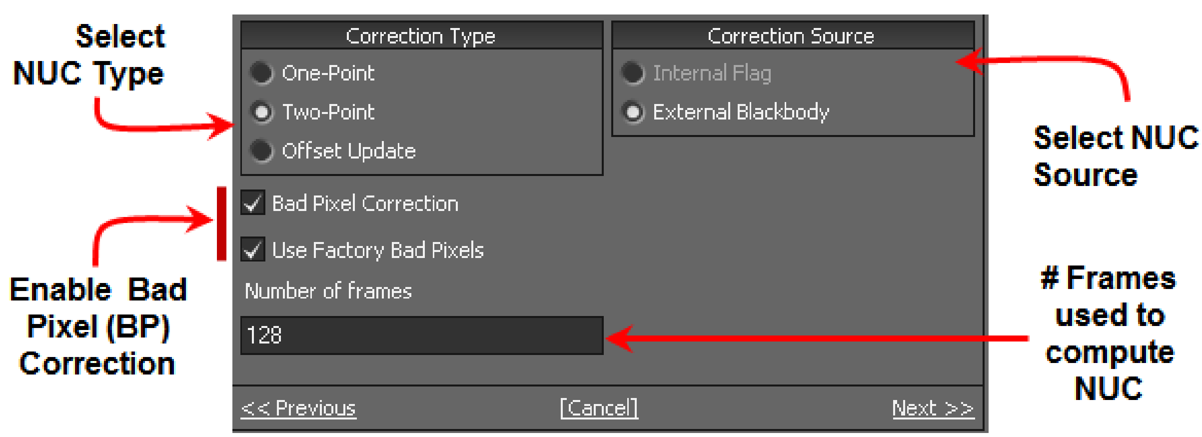
The default setting is to “Load Table Only”, in which case only the NUC coefficients are used from a NUC file. When the user selects “Load Table and the Following Settings”, the user can select which parameters from the NUC will override the current state. The option will not affect NUCs that are currently loaded into RAM, only those NUCs that are subsequently loaded from Flash memory. Unless a new state is saved, these override settings will not be remembered after a power cycle.

Performing a NUC

To build a NUC table using the camera electronics, select the *Perform Correction* icon  to start the NUC Wizard for the desired preset.

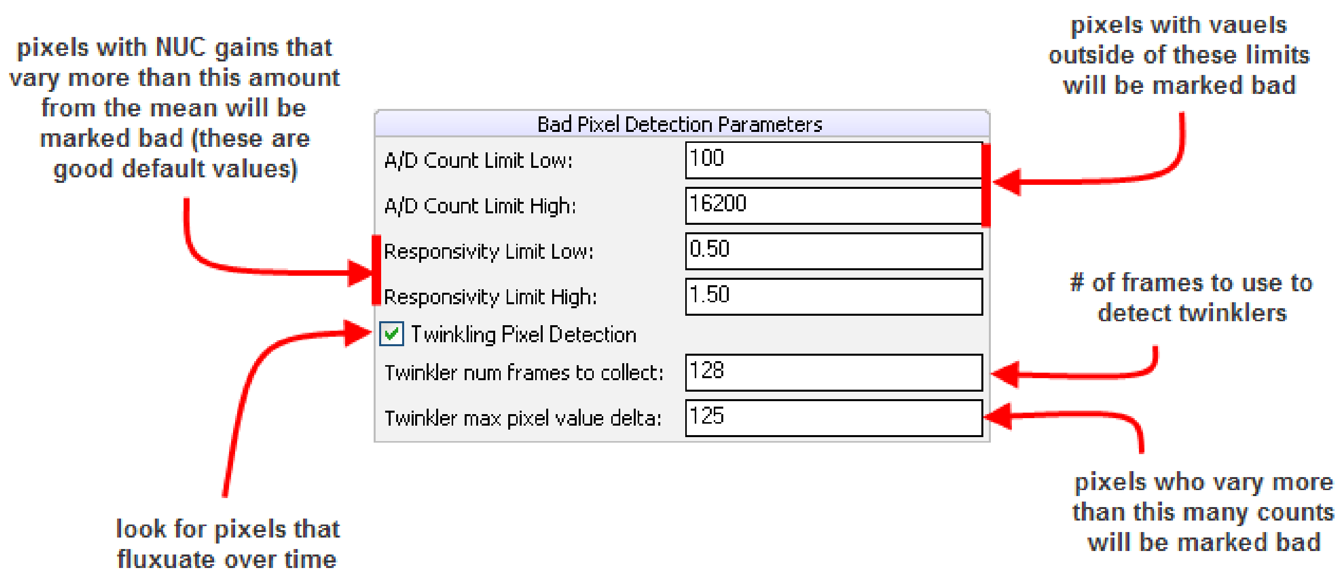
NOTE: Due to differences in camera electronics and FPA timings it is important to perform the NUC with the camera operating modes configured as it will be used when imaging.

After selecting the *Perform Correction* a second window comes up to allow the user to select correction parameters. When all selections have been made, click *Next>>* to continue.

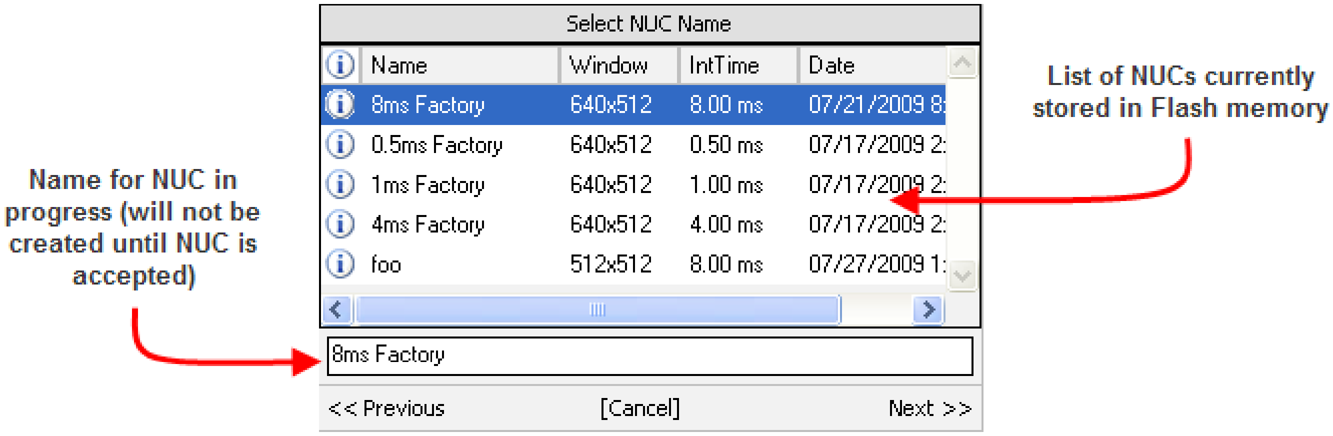


Correction (NUC) Types	
One Point	Sets the gain terms to “1” and computes the offset terms. Uses a single NUC source. Does not compute a BP correction.
Two Point	Sets both the gain and offset terms. Uses two NUC sources. Computes a bad pixel correction.
Offset Update	Retains the current NUC gain terms and updates the offset terms. Uses a single NUC source. Retains the current bad pixel (BP) correction.
Correction Sources	
Internal Flag	Use the internal flag as the NUC source. Because the flag is not temperature controlled, it can only be used for 1-point and Offset Update NUC functions
External Blackbody	Use an external blackbody as the NUC source. Program will prompt the user to place each source in front of the camera. NUC source needs to fill the entire field of view.
Number of frames	Set the number of to average when computing NUC coefficients. 16 frames is the default and works well for most scenarios. The value can be to be 2, 4, 8, 16, 32, 64, or 128.

After configuring the correction parameters and selecting *Next>>* the next window allows the user to set up the parameters used for the Bad Pixel Detection. Once the parameters are set, select *Next>>* to continue.

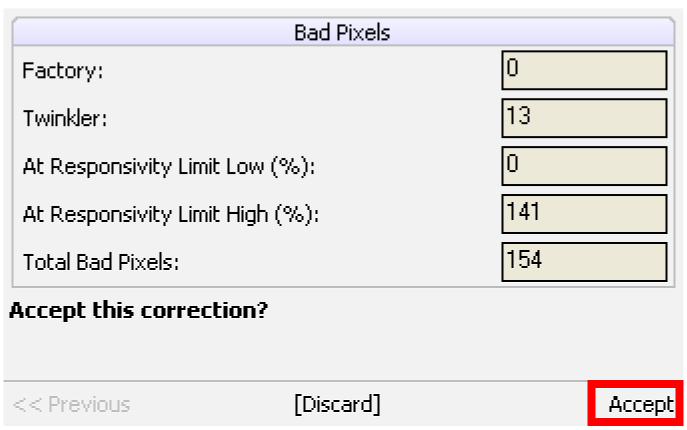


The next window allows the user to name the NUC. Simply type in the name for the table in the text box or select a previously saved file to replace it. Select *Next>>* to continue.



The next two screens will collect data from the NUC sources. If using the internal flag you will only see a few status messages. If using external blackbodies you will be prompted. After each step, click *Next>>* to continue.

The last screen gives a report of the bad pixels found. The dialog shows how many pixels failed in each category. If the result is satisfactory, click Accept to save the NUC. The NUC table will be stored to flash memory and loaded into RAM memory for that preset. If the NUC is poor and you want to abort, click *[Discard]*.



NOTE: It is possible for a bad pixel to fail more than one category, so the total bad pixels may be less than the sum of each category. “Factory” bad pixels are those that were determined to be bad during camera production testing.

What is a Non-Uniformity Correction (NUC)?

Non-Uniformity Correction (NUC) refers the process by which the camera electronics correct for the differences in the pixel-to-pixel response for each individual pixel in the detector array. The camera can create (or allow for the user to load) a Non-Uniformity Correction (NUC) table which consists of a unique gain and offset coefficient and a bad pixel indicator for each pixel. The table is then applied in the digital processing pipeline as shown in Figure 4-12. The result is corrected data where each pixel responds consistently across the detector input range creating a uniform image.

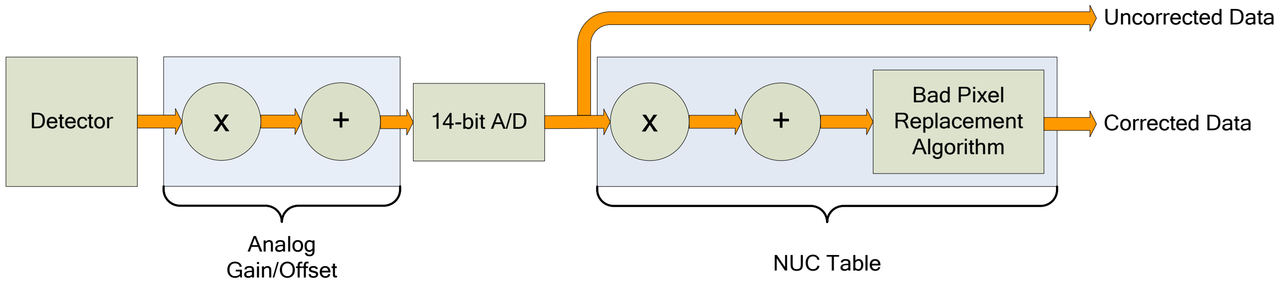


Figure 4-12: Digital Process Showing NUC Table Application

To create the NUC table, the camera images either one or two uniform temperature sources. The source can be an external source provided by the user or the camera's internal NUC flag which is basically a shutter the camera places in front of the detector. If the source is external it should be uniform and large enough to overfill the cameras field-of-view (FOV). By analyzing the pixel data from these constant sources, the non-uniformity of the pixels can be determined and corrected. There are three types of processes which are used to create the NUC table; One-Point, Two-Point, and Offset Update.

5.1.5.1.1 One-Point Correction Process

A One-Point Correction Process requires one uniform source, which is typically in the middle of the usable range. The One-Point Correction replaces all gain coefficients in the NUC table with a value of one ("1") as seen in Figure 4-13. The offset coefficients are computed uniquely for each pixel.

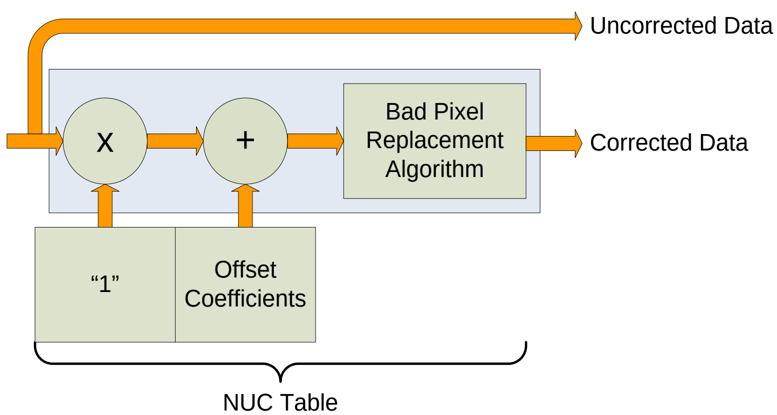


Figure 4-13: One-Point Correction

5.1.5.1.2 Two-Point Correction Process

The Two-Point Correction Process builds a NUC table that contains an individually computed gain and offset coefficient for each pixel as seen in Figure 4-14. Two uniform sources are required for this correction. One source at the low end and a second source at the upper end of the usable detector input range. Because of the use of two images at either end of the input range, the Two-Point Correction yields better correction results verses the One-Point process. A 2-point correct will also work better over a wider range of scene temperatures than a 1-point correction.

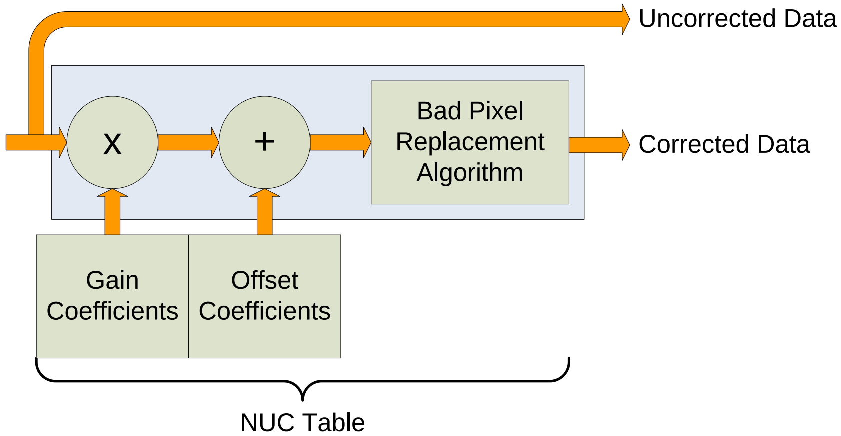


Figure 4-14: Two-Point Correction

5.1.5.1.3 Offset Update

Often times during the normal operation of a camera the electronics and/or optics will heat up or cool down which changes the uniformity of the camera image. This change requires a new NUC. However, this change is mainly in the offset response of the image while the gain component stays constant. An Offset Update simply computes a new offset coefficient using the existing gain coefficient and corrects the image non-uniformity. Offsets Update are typically performed when a Two-Point NUC table is being used.

An Offset Update requires only one uniform source, usually set at a temperature on the lower edge of the operational range.

5.1.5.1.4 Bad Pixel Correction

Within the NUC table there is an indication as to whether or not a pixel has been determined to be bad as seen in Figure 4-15. There are two methods the A6600 uses to determine bad pixels.

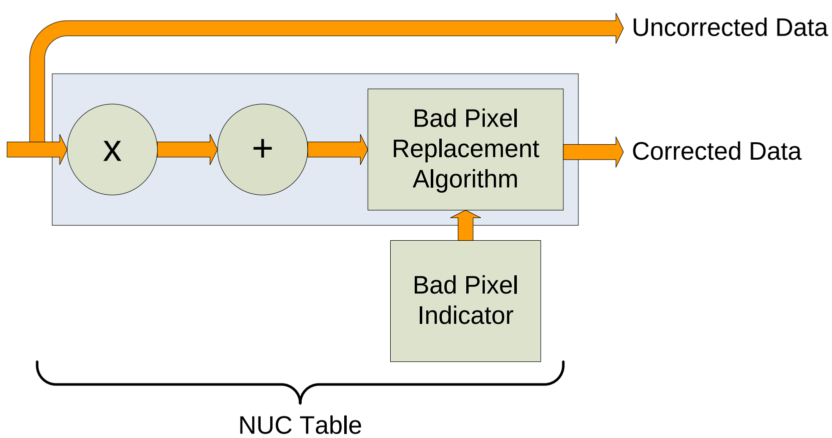


Figure 4-15: Bad Pixel Correction

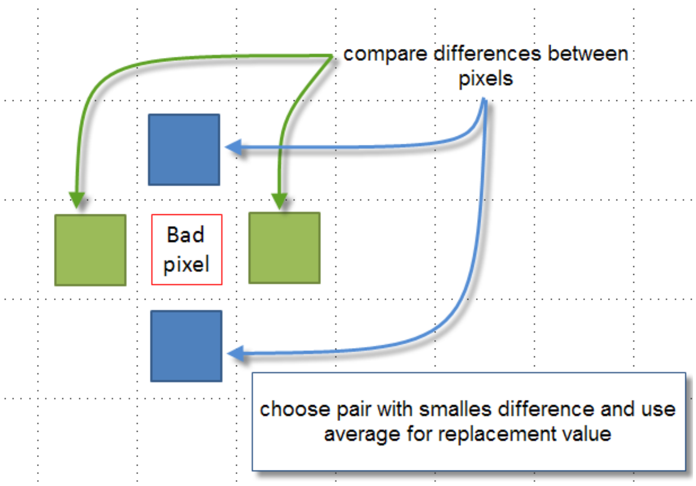
First, the NUC table gain coefficients are compared to a user defined acceptance boundary, *Responsivity Limit Low/High (%)*. The responsivity of a pixel can be thought of as the gain of that pixel. The gain coefficient in the NUC Table is a computed value that attempts to correct the individual pixel gain, or responsivity, to a normalized value across the array. Since the responsivity value directly relates to the gain coefficient in the NUC table, the A6600 can scan the NUC table gain coefficients and use them to determine if a pixel's responsivity exceeds the limits as set by the user.

The second method of determining bad pixels is to search for twinklers. Twinklers are pixels that have responsivity values within normal tolerances, but still exhibit large swings for small input changes. These pixels are on the "verge" of being bad and often appear to be noisy. To find these types of pixels the camera collects N number of frames and records the maximum and minimum values across that sample set for each pixel. If the delta between max and min exceeds the *Twinkler max pixel value delta* then the pixel is determined to be bad.

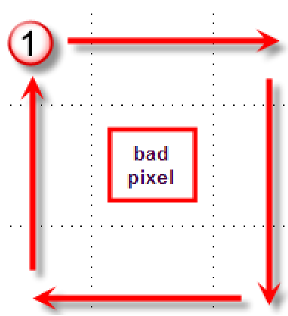
Since the responsivity test requires a gain coefficient, it is useless on NUC tables determine by the One-Point Correction because those tables have a value of one ("1") as the gain coefficients. The Twinkler test can be done on either correction process.

The A6600 uses two algorithms for bad pixel replacement: 2-point Gradient, and Nearest Neighbor.

The 2-point gradient algorithm is the default bad pixel correction method. With this algorithm, the two pairs of pixels above and below and to the left and right of the bad pixel are evaluated. The algorithm compares the differences between the pixels and chooses the pair with smallest gradient (difference). It then averages the two adjacent pixels and uses that value for the replacement value. This algorithm is better at handling bad pixels near a high contrast edge and is the default method. If the algorithm encounters a situation is cannot solve (for example, an edge or corner) it will fall back on the nearest neighbor algorithm.

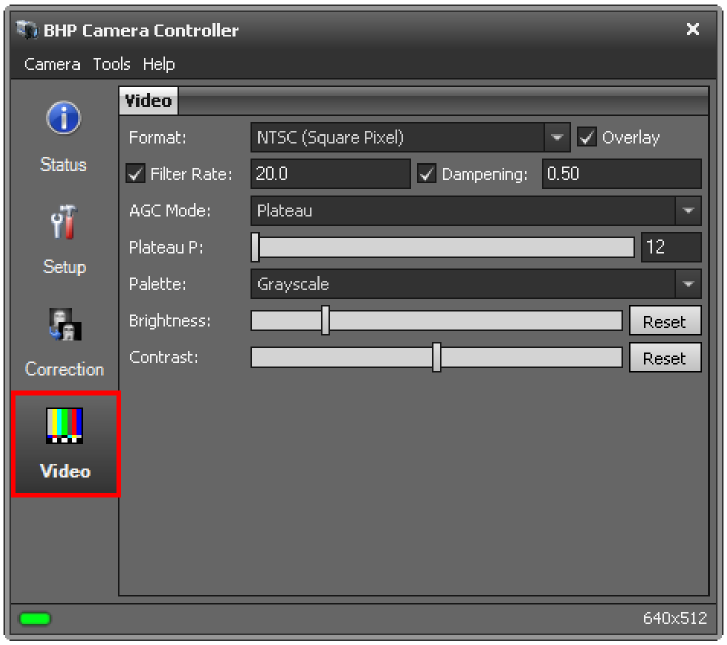


Nearest neighbor uses a simple replacement using an adjacent pixel. The adjacent pixel is picked using the pattern depicted below. When a bad pixel is near an edge, those search positions are skipped.



5.1.6 Video Page

The A6600 camera has a 14-bit digital output. However, the analog output is only 8-bit. An Automatic Gain Control (AGC) algorithm is used to map the 14-bit digital to the 8-bit analog data. The Video Tab provides controls related to optimizing the Analog video output. **These controls affect only the analog video**. Figure 4-16 shows a flow chart of the analog video process and how the parameters of this screen are used.



Analog Video Setup Options	
Format	**NTSC:** 640x480, 30Hz interlaced, color based on Palette selection, *(Note: top and bottom 16 lines are truncated when full images are displayed. The Analog window can be adjusted +/- 16 rows using the Setup>>Window Tab)* **PAL:** 640x480, 25Hz interlaced, color based on Palette selection *Note: When camera frame size is smaller than video frame size, black borders are added to maintain standard video output sizes*
Overlay	Enables the analog video overlay.
Filter Rate	Rate at which AGC is computed (1 to 20 Hz)
Dampening	Rate at which AGC is allowed to change. This will keep the AGC from responding rapidly to fast tridents changes. Specified as a fraction from 0 to 1. This fraction is used as a weighting factor for the current AGC vs. the newly computed AGC.

Analog Video Setup Options	
AGC Mode	Plateau: Uses a plateau equalization (PE) algorithm to scale the image data for video display DDE: Digital Detail Enhancement. Manual Linear: Scales the image data to a windowed section of data range as set by the user Auto Linear: Same as Manual Linear except camera analyzes image and sets limits at ~1% and 98% of the histogram.
Plateau P Bounds	Scaling factor for the Plateau Equalization function Note: Plateau P is only visible when AGC Mode>>Plateau is selected Sets the lower and upper data range to be scaled to on the video data. Note: Bounds is only visible when AGC Mode>>Manual Linear is selected
DDE Sharpness	Only visible when AGC is set to DDE. Selects the amount of enhancement processing.
Palette	Allows user to select the color scheme to use on the analog video channel.
Brightness and Contrast	Allows user to set brightness and contrast on the video encoder. As shown in Figure 4-16, this occurs after the digital data has been scaled and converted to analog. These controls don't tend to have as much effect as the controls that are applied to the digital side (before the video encoder).

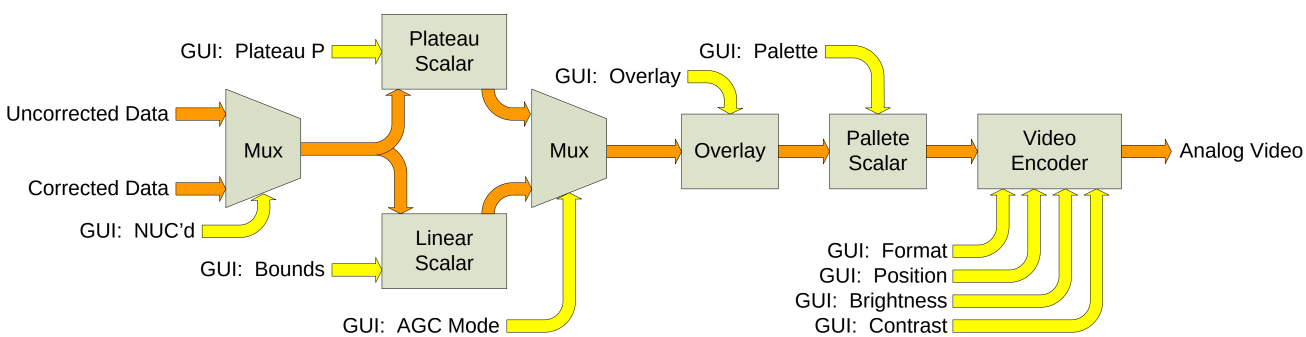
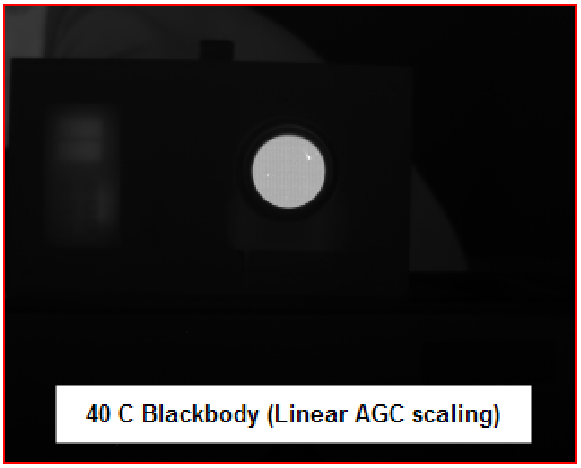
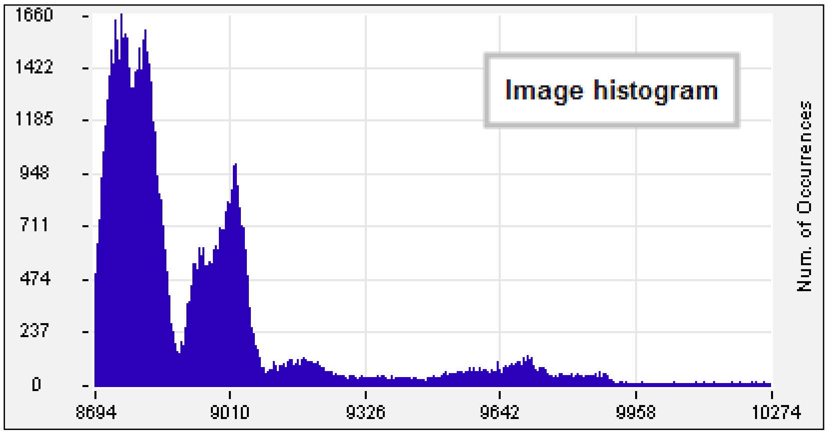
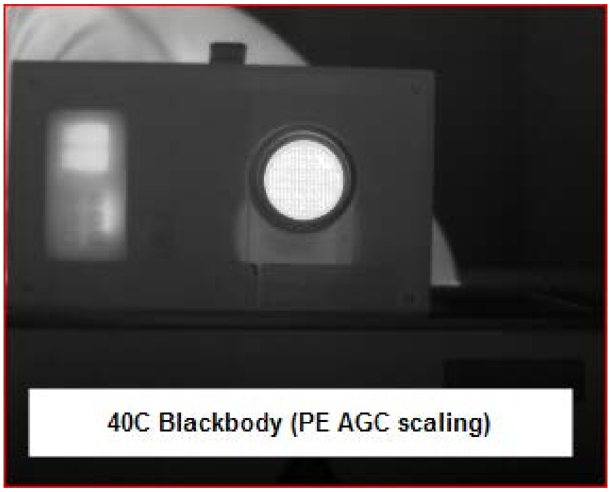


Figure 4-5: *Analog Video Flow*

The Manual Linear algorithm evenly distributes the grayscale values over the digital values. This works fairly well if the image dynamic range is fairly evenly distributed but in general does not produce high contrast imagery, but it also does not saturate or clip the hot and cold regions either. The Plateau Equalization algorithm (also called PE) is a nonlinear AGC algorithm that uses the image histogram to optimally map the 256 gray scales. This algorithm works well for most scenes but it works best when the scene has a "bi-modal" distribution (two clumps). It usually the most popular because algorithm because it produces high contrast (but more saturated) video. The following pictures illustrate the differences in AGC algorithms. (The data was captured from the digital output but the effect is similar for the analog side.)







One final note about the PE algorithm. It is very aggressive. It can pull detail out of very low contrast imagery. It can also pull out some very low-level NUC and FPA artifacts and noise if the contrast is low enough. This does not necessarily mean there is a problem with the camera, or NUC.

6 Interfaces

6.1 Mechanical (dimensions in inches)

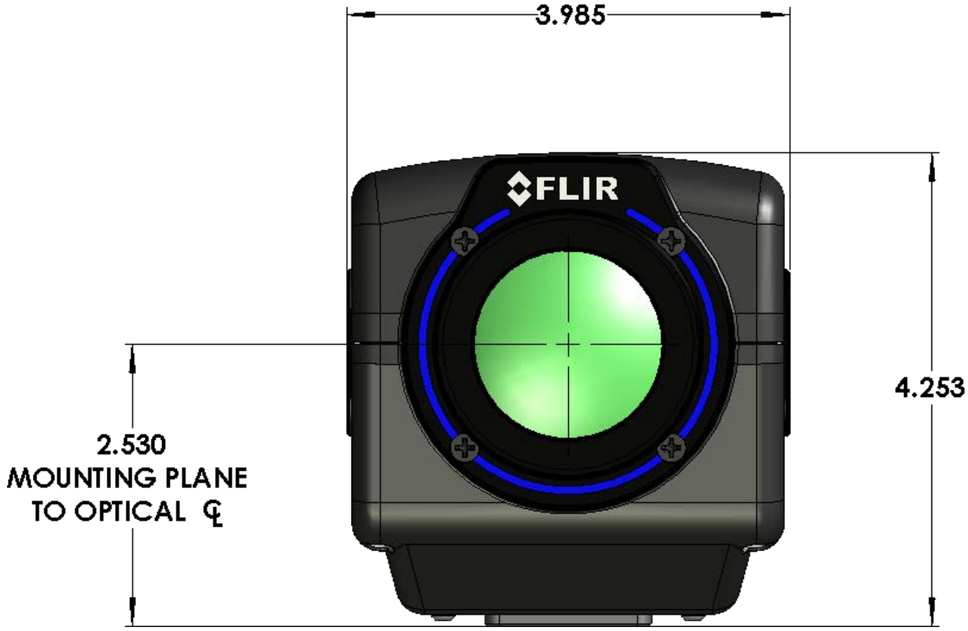


Figure 6-1: Front view of A6600

Figure 6-2: Side view of A6600 with 50mm lens

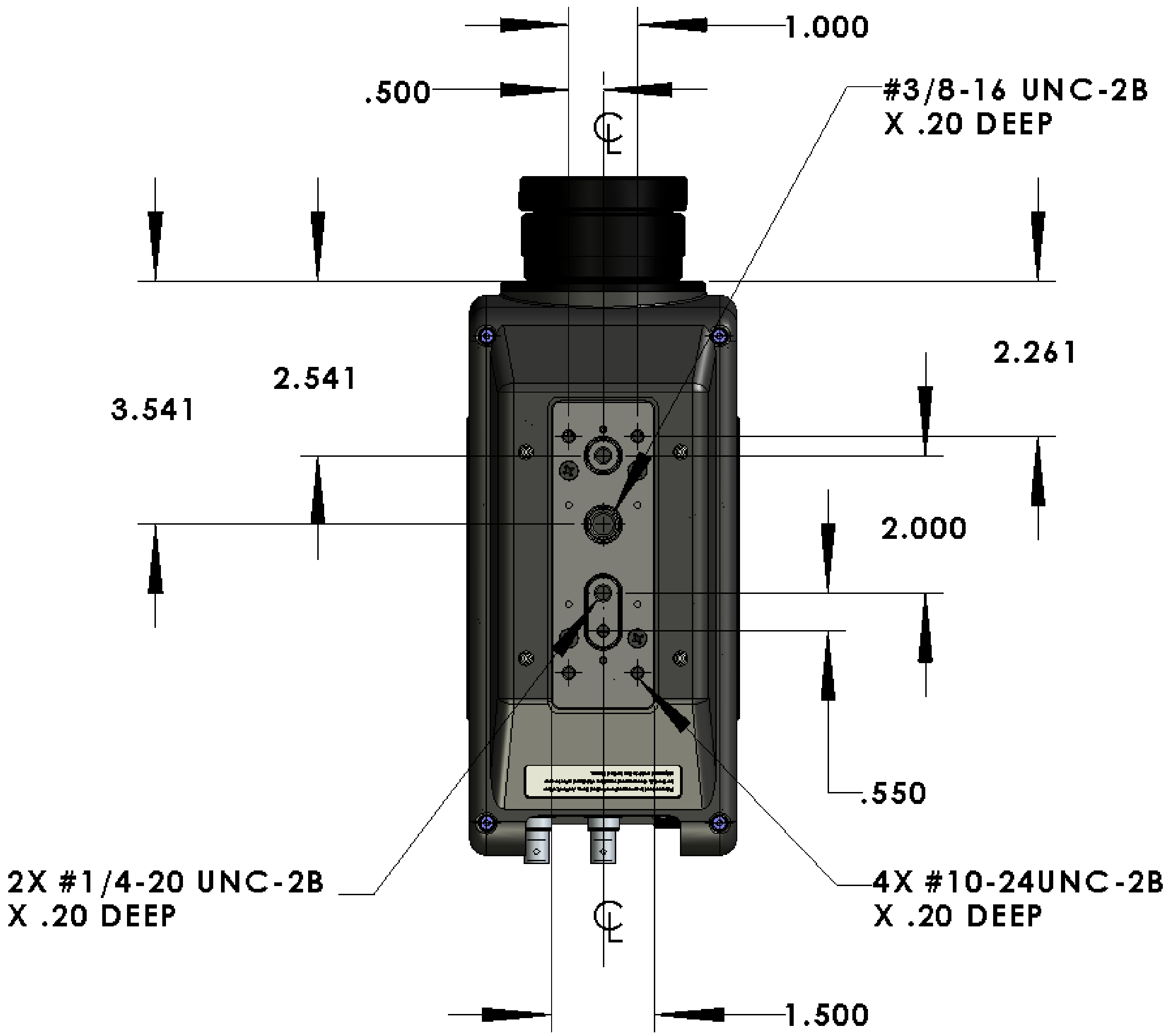
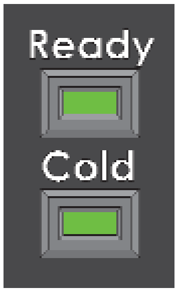


Figure 6-1: Bottom view of A6600

6.1.1 Status Lights

The A6600 provides a set of status indicators on the back panel to give the user some visual feedback on the camera operating state.

	POWER (on power switch): Indicates that the camera is ON.
	READY: Camera electronics have completed boot up. Camera is ready to accept commands.
	COLD: Indicates that the FPA has reached operating temperature (<80K).

6.1.2 Power Interface

24V DC nominal, external AC-DC power converter is provided with the A6600 camera system as a standard accessory. Power supply specifications are:

Input voltage range: 100-250VAC 50/60Hz

Current draw: 24 VDC at up to 4.0 amps input to the camera

Converter dimensions: 6.25 inches x 3.5 inches x 2.75 inch (L x W x H)

Converter weight: approximately 1 lb

The power input pinouts are shown in Figure 6-4.

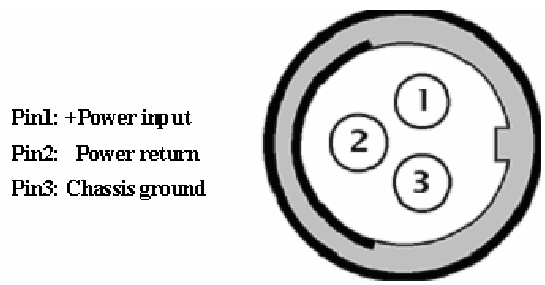


Figure 6-4: A6600 Power Input Pinouts

When using your own DC power supply, you should take note of the following information:

Output voltage: 24 VDC

Current draw: 1.4 amps nominal steady state, 2.6 amps peak (during cooldown)

A6600 power dissipation is <50 Watts steady state at nominal ambient temperature.

Mating Connector: Fisher Connectors, S103A052-130+E31 103.1/5.7 +B. (FLIR PN 26399-000). The power cable should be 20AWG (stranded 10/30), 3 conductor, no shield, max diameter of 0.223 inches. (Example: Alphawire PN 882003)

6.1.3 Other Interfaces

6.1.3.1 Gigabit Ethernet

Gigabit Ethernet (GigE) is a common interface found in most PC's. The GigE interface can be used for image acquisition and/or camera control. The GigE interface is GigE Vision and Genicam compliant

6.1.3.2 Sync In

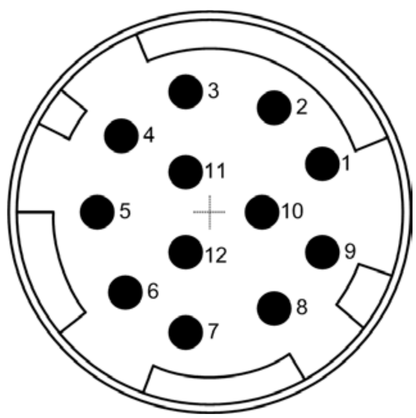
The Sync In can be selected, by the user, to operate as an external clock It is a rising edge LV-CMOS signal (5.5V max). The minimum width is 160nS.

6.1.3.3 Video

Composite video out (BNC connector). User selectable to be NTSC standard (640x480, 30Hz interlaced) or PAL standard (640x512, 25Hz interlaced). Video supports user selectable color palettes.

6.1.3.4 AUX Connector [A6650 only]

The AUX connector provides access to additional signals. The diagram below shows a closeup view of the rear panel connector.



A breakout cable is provided with all A6650 cameras.

The provided breakout cable has numerical markings on the BNC overmolding that are described in the table below.

Pin	Name	Breakout Connector	Type	Description
1	NC			
2	NC			
3	RECORD START	BNC 3	INPUT	Sets bit in image header. Can be used by ResearchIR to start recording.
4	SYNC OUT	BNC 4	OUTPUT	160ns wide pulse at start of integration
5	GROUND			
6	GPIO IN	BNC 6	INPUT	Sets bits in image header. Updated at ~1Hz rate.
7	Reserved	BNC 7		
8	TRIGGER	BNC 8	INPUT	External trigger. Can be used by ResearchIR to start recording.
9	Reserved	BNC 9		
10	SYNC IN	BNC 10	INPUT	Duplicate of rear panel input. Do not use both at the same time.
11	RS-232 TX	DB9 Male	OUTPUT	For camera control
12	RS-232 RX	DB9 Male	INPUT	For camera control
Inputs are all LV-CMOS. High>2V, Low<0.2V. Max is 5.5V				

If you wish to make your own breakout cable, there are three variants of the Hirose mating connector that will work: HR10A-10P-12S(73), HR10-10P-12S(73) or HR10A-10P-12SC(73).

7 Specifications

7.1 Interface

AC Power	90-230V_{AC}, 50-60 Hz (using FLIR 24123-000 power supply)
Control	Genicam over Gigabit Ethernet (10/100/1000)
Analog Video Out	Selectable • NTSC/PAL selectable, BNC, 75Ω, 1V pk-pk
Frame Sync In	LVCMOS singled ended, BNC, selectable polarity, >160ns pulse width
Digital Video Out	14-bit Gigabit Ethernet (GigE Vision 2.0)
Optical Interface	Bayonet
Thermal Interface	Semi-sealed enclosure with integral forced air heat exchanger
Mechanical Interface	2 (two) ¼-20 tripod screws; 1 (one) 3/8-16 professional tripod screw; 4 (four) 10-24 mount holes

7.2 Windowing Capacity

Window Sizes	640x512, 320x256, 160x120, [flexible for A6650]
Windowing Step Size	16 columns, 4 rows (A6650)
Window Offset Step Size	No offset, FPA centered

7.3 Acquisition Modes and Features

Frame Rate :	
Max at Full Window	60 Hz for A6700, 125Hz for A6650
Max w/ Windowing	240 Hz @ ½ window, 480 Hz @ ¼ window (A6600)
	406 Hz @ ½ window, 1063 Hz @ ¼ window (A6650)
Max @ Min Window	4175 Hz @ 16x4 (A6650)
Minimum	1.45mHz
Resolution	160nS
Pixel Rate (burst)	50 MHz
Integration Width	
Maximum	98% selected frame time (1/frame rate)

Minimum **Resolution**	480 nS 160 nS
Preset Sequencing	• N/A
Digital Video Output	Selectable: • Raw digital video (14-bits) • Gain and offset (NUC) corrected (14-bits) • NUC with bad pixel replaced (14-bits)

7.4 Analog Video

Video Output	• NTSC or PAL composite
Data Output	Selectable • Raw, uncorrected • Corrected
AGC	Selectable • DDE • Plateau based equalization • Linear equalization
AGC Filter	User controlled damping factor User controlled update rate
Overlay	Available on analog output
Palettes	Selectable • Grayscale • Various color palettes
Zoom (Analog video)	Auto-selected • x1 for 640x512 • x2 for 320x256 and 160x120 window sizes
Brightness and Contrast (analog video)	User controlled to increase or decrease

7.5 Performance Characteristics

Power Consumption **FLIR PWR Supply @ 120V$_{AC}$**	Continuous Cool Down: Continuous Normal:	50 VA 41 VA

Power Consumption **Camera DC Power @ 24V$_{DC}$**	Continuous Cool Down: Continuous Normal:	24 Watts 21.25 Watts
Cool-down Time	≈7 minutes to reach operating temperature	
Sensitivity (w/o optics) **NEΔT**[1]	18 mK typ.	

1) NEΔT is at 50% nominal bucket fill, 298K background, ± 5°C signal

7.6 Non Uniformity Correction

NUC Types	One Point (offset value with unity gain) Two Point (offset and gain values) non-volatile Two Point w/Bad Pixel Detection/Replacement Update Offset (recalculates offset using current gain)
NUC Source	Internal: Ambient flag (for 1-pt and offset update only) External: Any user supplied source which covers entire FOV
Bad Pixel Replacement	Two-Point Gradient and nearest neighbor (autoselected)
Number of NUC's	4 active NUC's in preset selectable form >100 NUCs in on-board flash
NUC Time	< 15 seconds
NUC Performance	0.1%

7.7 Detector/FPA

Spectral Response	3-5um (1-5um for broadband models)
Detector Type	InSb
f/#	f/2.5 or f/4
Integration Mode	Snapshot
Format (HxV)	640 x 512
Operability	>99.8%, 99.95% typical
Charge Handling Capacity[1]	7.2 x10^6 e-
Detector Pitch	15 microns
Detector Cooling	Rotary Cryo Cooler

7.8 General Characteristics

Size	
Length	8.5 inches
Width	4.0 inches
Height	4.3 inches
	(not including lens or lens cover)
Weight	5 lbs (not including lens or lens cover)
Temperature	
Operating	-40C to +50C
Storage	-55C to +80C
Shock	40 g's, 11 msec half sine pulse
Vibration	4.3 g's RMS random vibration, all three axes
Humidity	<95% relative humidity, non-condensing
Altitude	0 to 10,000 feet operational, 0 to 70,000 feet non-operational
Operating Orientation	No restriction in orientation

8 Maintenance

8.1 Camera and Lens Cleaning

8.1.1 Camera Body, Cables and Accessories

The camera body, cables and accessories may be cleaned by wiping with a soft cloth. To remove stains, wipe with a soft cloth moistened with a mild detergent solution and wrung dry, then wipe with a dry soft cloth.

Do not use benzene, thinner, or any other chemical product on the camera, the cables or the accessories, as this may cause deterioration.

8.1.2 Lenses

It is recommends that all optics be handled with care and the need for cleaning is eliminated or at least reduced. If however,cleaning is deemed necessary, the methods herein are accepted industry standards and should yield good results.

Before you BEGIN,

Identify the type of optic to be cleaned.

- Is it hard or soft material?
- Is it coated & with what?

How is it contaminated?

- Particulate or film or both.

Set a standard of cleanliness.

- What is clean enough?
- Establish & document a standard.

Know your solvent.

- Read the MSDS
- See recommended solvents

Assemble your supplies:

- Latex gloves
- Clean, well-lit work area
- Inspection light
- Lens tissue or cloth
- Dust bulb or filtered air
- Proper solvent
- Solvent dispenser

<u>The Drag Wipe Method</u>:

Set-up a clean area to work from with an anti-roll barrier around the edge to prevent anything from leaving the table.

Use a clean, lint free cloth or lens tissue.

Wear latex gloves - clean them with alcohol or detergent before handling optic.

NEVER touch the face of the optic.

Cover the optic and store in a dry - dust free area immediately after cleaning.

1. Blow or brush loose particles from surface. Don't let them contaminate your work area. Use air from a can or a filtered source.
2. Apply solvent directly to your cloth. Use slow, even, light pressure working from edge to edge across the optic.

Recommended Solvents

Material	Solvent		
Fused Silica	1,2,3,4	Zinc Selenide	1,2,4
BK-7	1,2,3,4	Zinc Sulfide	1,2,4
Optical Crown Glass	1,2,3,4	Sapphire	1,2,3,4
Zerodur	1,2,3,4		
Calcium Fluoride	1,2,4	Coated Optics	
Magnesium Fluoride	1,2,4	Dielectric coating	1,2,3,4
Sodium Chloride	Nitrogen	Interference filters	3
Potassium Chloride	Nitrogen	Soft metallic coating	Air only
Potassium Bromide	Nitrogen	Hard/Protected metallic	1,2,3,4
Thallium Bromoiodide	Nitrogen		

1] Water free Acetone

2] Ethanol

3] Methanol

4] Isopropanol

9 Infrared Primer

9.1 History of Infrared

Less than 200 years ago the existence of the infrared portion of the electromagnetic spectrum wasn't even suspected. The original significance of the infrared spectrum, or simply 'the infrared' as it is often called, as a form of heat radiation is perhaps less obvious today than it was at the time of its discovery by Herschel in 1800.

Figure 8-1: Sir William Herschel (1738–1822)

The discovery was made accidentally during the search for a new optical material. Sir William Herschel – Royal Astronomer to King George III of England, and already famous for his discovery of the planet Uranus – was searching for an optical filter material to reduce the brightness of the sun's image in telescopes during solar observations. While testing different samples of colored glass which gave similar reductions in brightness he was intrigued to find that some of the samples passed very little of the sun's heat, while others passed so much heat that he risked eye damage after only a few seconds' observation.

Herschel was soon convinced of the necessity of setting up a systematic experiment, with the objective of finding a single material that would give the desired reduction in brightness as well as the maximum reduction in heat. He began the experiment by actually repeating Newton's prism experiment, but looking for the heating effect rather than the visual distribution of intensity in the spectrum. He first blackened the bulb of a sensitive mercury-in-glass thermometer with ink, and with this as his radiation detector he proceeded to test the heating effect of the various colors of the spectrum formed on the top of a table by passing sunlight through a glass prism. Other thermometers, placed outside the sun's rays, served as controls.

As the blackened thermometer was moved slowly along the colors of the spectrum, the temperature readings showed a steady increase from the violet end to the red end. This was not entirely unexpected, since the Italian researcher, Landriani, in a similar experiment in 1777 had observed much the same effect. It was Herschel, however, who was the first to recognize that there must be a point where the heating effect reaches a maximum, and those measurements confined to the visible portion of the spectrum failed to locate this point.

Figure 8-2: Marsilio Landriani (1746–1815)

Moving the thermometer into the dark region beyond the red end of the spectrum, Herschel confirmed that the heating continued to increase. The maximum point, when he found it, lay well beyond the red end – in what is known today as the ‘infrared wavelengths’.

When Herschel revealed his discovery, he referred to this new portion of the electromagnetic spectrum as the ‘thermometrical spectrum’. The radiation itself he sometimes referred to as ‘dark heat’, or simply ‘the invisible rays’. Ironically, and contrary to popular opinion, it wasn't Herschel who originated the term ‘infrared’. The word only began to appear in print around 75 years later, and it is still unclear who should receive credit as the originator.

Herschel’s use of glass in the prism of his original experiment led to some early controversies with his contemporaries about the actual existence of the infrared wavelengths. Different investigators, in attempting to confirm his work, used various types of glass indiscriminately, having different transparencies in the infrared. Through his later experiments, Herschel was aware of the limited transparency of glass to the newly-discovered thermal radiation, and he was forced to conclude that optics for the infrared would probably be doomed to the use of reflective elements exclusively (i.e. plane and curved mirrors). Fortunately, this proved to be true only until 1830, when the Italian investigator, Melloni, made his great discovery that naturally occurring rock salt (NaCl) – which was available in large enough natural crystals to be made into lenses and prisms – is remarkably transparent to the infrared. The result was that rock salt became the principal infrared optical material, and remained so for the next hundred years, until the art of synthetic crystal growing was mastered in the 1930’s.

Figure 8-3: Macedonio Melloni (1798–1854)

Thermometers, as radiation detectors, remained unchallenged until 1829, the year Nobili invented the thermocouple. (Herschel’s own thermometer could be read to 0.2 °C (0.036 °F), and later models were able to be read to 0.05 °C (0.09 °F)). Then a breakthrough occurred; Melloni connected a number of thermocouples in series to form the first thermopile. The new device was at least 40 times as sensitive as the best thermometer of the day for detecting heat radiation – capable of detecting the heat from a person standing three meters away.

The first so-called ‘heat-picture’ became possible in 1840, the result of work by Sir John Herschel, son of the discoverer of the infrared and a famous astronomer in his own right. Based upon the differential evaporation of a thin film of oil when exposed to a heat pattern focused upon it, the thermal image could be seen by reflected light where the interference effects of the oil film made the image visible to the eye. Sir John also managed to obtain a primitive record of the thermal image on paper, which he called a ‘thermograph’.

Figure 8-4: Samuel P. Langley (1834–1906)

The improvement of infrared-detector sensitivity progressed slowly. Another major breakthrough, made by Langley in 1880, was the invention of the bolometer. This consisted of a thin blackened strip of platinum connected in one arm of a Wheatstone bridge circuit upon which the infrared radiation was focused and to which a sensitive galvanometer responded. This instrument is said to have been able to detect the heat from a cow at a distance of 400 meters.

An English scientist, Sir James Dewar, first introduced the use of liquefied gases as cooling agents (such as liquid nitrogen with a temperature of -196 °C (-320.8 °F)) in low temperature research. In 1892 he invented a unique vacuum insulating container in which it is possible to store liquefied gases for entire days. The common ‘thermos bottle’, used for storing hot and cold drinks, is based upon his invention.

Between the years 1900 and 1920, the inventors of the world ‘discovered’ the infrared. Many patents were issued for devices to detect personnel, artillery, aircraft, ships – and even icebergs. The first operating systems, in the modern sense, began to be developed during the 1914–18 war, when both sides had research programs devoted to the military exploitation of the infrared. These programs included experimental systems for enemy intrusion/detection, remote temperature sensing, secure communications, and ‘flying torpedo’ guidance. An infrared search system tested during this period was able to detect an approaching airplane at a distance of 1.5 km (0.94 miles), or a person more than 300 meters (984 ft.) away.

The most sensitive systems up to this time were all based upon variations of the bolometer idea, but the period between the two wars saw the development of two revolutionary new infrared detectors: the image converter and the photon detector. At first, the image converter received the greatest attention by the military, because it enabled an observer for the first time in history to literally ‘see in the dark’. However, the sensitivity of the image converter was limited to the near infrared wavelengths, and the most interesting military targets (i.e. enemy soldiers) had to be illuminated by infrared search beams. Since this involved the risk of giving away the observer’s position to a similarly-equipped enemy observer, it is understandable that military interest in the image converter eventually faded.

The tactical military disadvantages of so-called 'active’ (i.e. search beam-equipped) thermal imaging systems provided impetus following the 1939–45 war for extensive secret military infrared-research programs into the possibilities of developing ‘passive’ (no search beam) systems around the extremely sensitive photon detector. During this period, military secrecy regulations completely prevented disclosure of the status of infrared-imaging technology. This secrecy only began to be lifted in the middle of the 1950’s, and from that time adequate thermal-imaging devices finally began to be available to civilian science and industry.

9.2 Theory of Thermography

9.2.1 Introduction

The subjects of infrared radiation and the related technique of thermography are still new to many who will use an infrared camera. In this section the theory behind thermography will be given.

9.2.2 The Electromagnetic Spectrum

The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called bands, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiation in the different bands of the electromagnetic spectrum. They are all governed by the same laws and the only differences are those due to differences in wavelength.

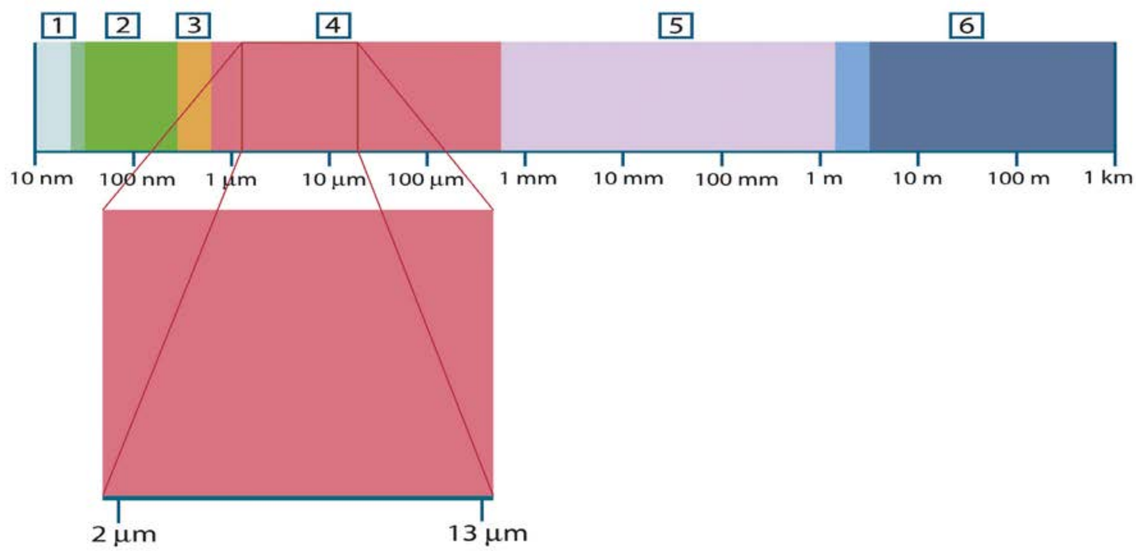


Figure 8-5 The Electromagnetic Spectrum

1: X-ray; 2: UV; 3: Visible; 4: IR; 5: Microwaves; 6: Radiowaves.

Thermography makes use of the infrared spectral band. At the short-wavelength end the boundary lies at the limit of visual perception, in the deep red. At the longwavelength end it merges with the microwave radio wavelengths, in the millimeter range.

The infrared band is often further subdivided into four smaller bands, the boundaries of which are also arbitrarily chosen. They include: the near infrared (0.75–3 µm), the middle infrared (3–6 µm), the far infrared (6–15 µm) and the extreme infrared (15–100 µm). Although the wavelengths are given in µm (micrometers), other units are often still used to measure wavelength in this spectral region, e.g. nanometer (nm) and Ångström (Å). The relationships between the different wavelength measurements is:

$$10\ 000\ \text{Å} = 1\ 000\ \text{nm} = 1\ \mu = 1\ \mu\text{m}$$

9.2.3 Blackbody Radiation

A blackbody is defined as an object which absorbs all radiation that impinges on it at any wavelength. The apparent misnomer black relating to an object emitting radiation is explained by Kirchhoff's Law (after Gustav Robert Kirchhoff, 1824–1887), which states that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation.

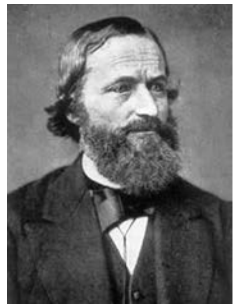


Figure 8-6: Gustav Robert Kirchhoff (1824–1887)

The construction of a blackbody source is, in principle, very simple. The radiation characteristics of an aperture in an isotherm cavity made of an opaque absorbing material represents almost exactly the properties of a blackbody. A practical application of the principle to the construction of a perfect absorber of radiation consists of a box that is light tight except for an aperture in one of the sides. Any radiation which then enters the hole is scattered and absorbed by repeated reflections so only an infinitesimal fraction can possibly escape. The blackness which is obtained at the aperture is nearly equal to a blackbody and almost perfect for all wavelengths.

By providing such an isothermal cavity with a suitable heater it becomes what is termed a cavity radiator. An isothermal cavity heated to a uniform temperature generates blackbody radiation, the characteristics of which are determined solely by the temperature of the cavity. Such cavity radiators are commonly used as sources of radiation in temperature reference standards in the laboratory for calibrating thermographic instruments, such as a FLIR Systems camera for example.

If the temperature of blackbody radiation increases to more than 525 °C (977 °F), the source begins to be visible so that it appears to the eye no longer black. This is the incipient red heat temperature of the radiator, which then becomes orange or yellow as the temperature increases further. In fact, the definition of the so-called color temperature of an object is the temperature to which a blackbody would have to be heated to have the same appearance. Now consider three expressions that describe the radiation emitted from a blackbody.

Planck's Law

Figure 8-7: Max Planck (1858–1947)

Max Planck (1858–1947) was able to describe the spectral distribution of the radiation from a blackbody by means of the following formula:

$$W_{\lambda b} = \frac{2\pi hc^3}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)} \times 10^{-6} \left[Watt/m^2 \mu m\right]$$

Where:

Wλb = Blackbody spectral radiant emittance at wavelength λ.

c = Velocity of light = 3 × 108 m/s

h = Planck's constant = 6.6 × 10-34 Joule sec.

k = Boltzmann's constant = 1.4 × 10-23 Joule/K.

T = Absolute temperature (K) of a blackbody.

λ = Wavelength (μm).

Note

The factor 10-6 is used since spectral emittance in the curves is expressed in Watt/m2m. If the factor is excluded, the dimension will be Watt/m2μm.

Planck's formula, when plotted graphically for various temperatures, produces a family of curves. Following any particular Planck curve, the spectral emittance is zero at λ = 0, then increases rapidly to a maximum at a wavelength λmax and after passing it approaches zero again at very long wavelengths. The higher the temperature, the shorter the wavelength at which maximum occurs.

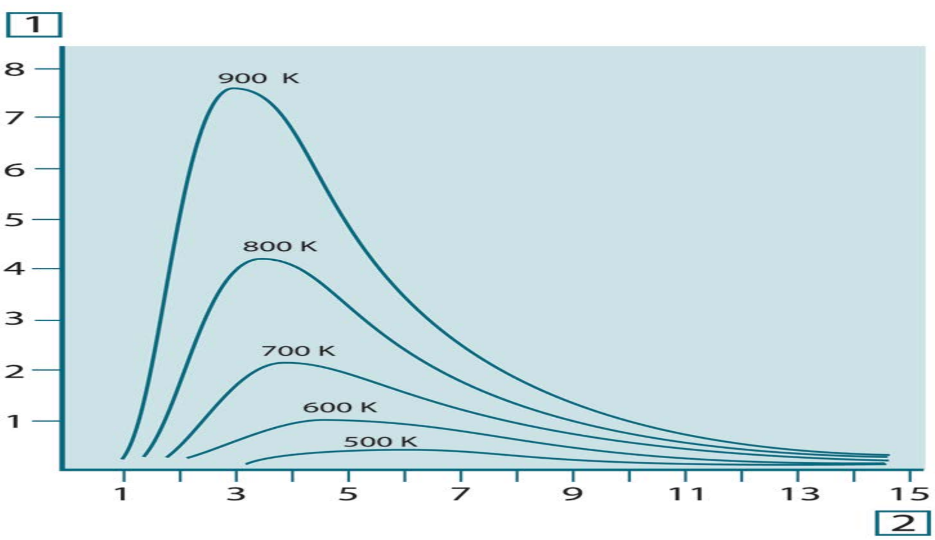


Figure 8-8: Blackbody spectral radiant emittance according to Planck's law, plotted for various absolute temperatures. 1: Spectral radiant emittance (W/cm2 × 103(μm)); 2: Wavelength (μm)

Wien's Displacement Law

By differentiating Planck's formula with respect to λ, and finding the maximum, we have:

$$\lambda_{\max} = \frac{2898}{T}[\mu m]$$

This is Wien's formula (after Wilhelm Wien, 1864–1928), which expresses mathematically the common observation that colors vary from red to orange or yellow as the temperature of a thermal radiator increases. The wavelength of the color is the same as the wavelength calculated for λmax. A good approximation of the value of λmax for a given blackbody temperature is obtained by applying the rule-of-thumb 3 000/T µm. Thus, a very hot star such as Sirius (11 000 K), emitting bluish-white light, radiates with the peak of spectral radiant emittance occurring within the invisible ultraviolet spectrum, at wavelength 0.27 µm.

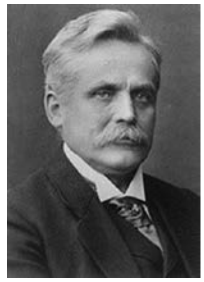


Figure 8-9: Wilhelm Wien (1864–1928)

The sun (approx. 6 000 K) emits yellow light, peaking at about 0.5 µm in the middle of the visible light spectrum.

At room temperature (300 K) the peak of radiant emittance lies at 9.7 µm, in the far infrared, while at the temperature of liquid nitrogen (77 K) the maximum of the almost insignificant amount of radiant emittance occurs at 38 µm, in the extreme infrared wavelengths.

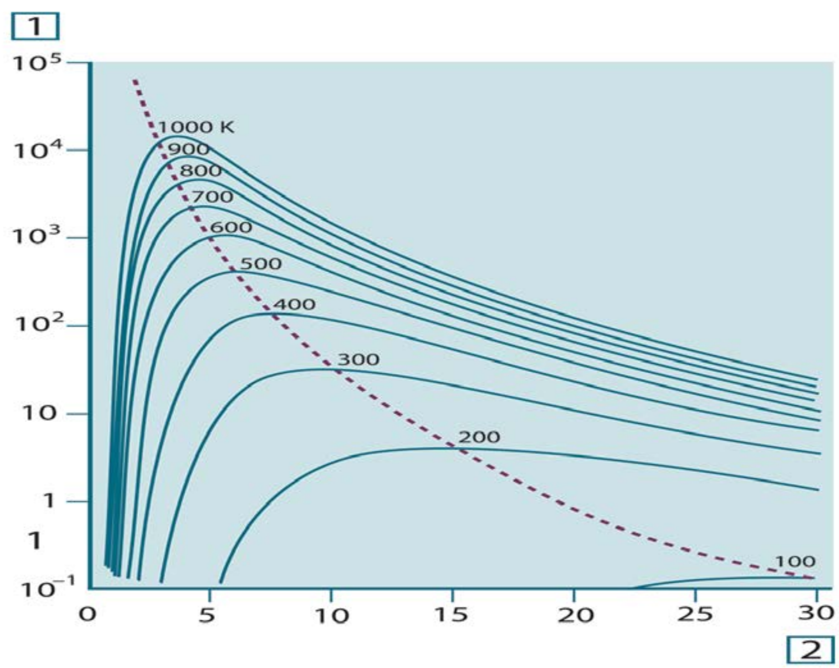


Figure 8-10: Planckian curves plotted on semi-log scales from 100 K to 1000 K. The dotted line represents the locus of maximum radiant emittance at each temperature as described by Wien's displacement law. 1: Spectral radiant emittance (W/cm2 (µm)); 2: Wavelength (µm).

Stefan-Boltzmann's Law

By integrating Planck’s formula from λ = 0 to λ = ∞, we obtain the total radiant emittance (Wb) of a blackbody:

$$W_b = \sigma T^4 \ \ [\mathrm{Watt/m^2}]$$

This is the Stefan-Boltzmann formula (after Josef Stefan, 1835–1893, and Ludwig Boltzmann, 1844–1906), which states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. Graphically, Wb represents the area below the Planck curve for a particular temperature. It can be shown that the radiant emittance in the interval $\lambda = 0$ to λmax is only 25 % of the total, which represents about the amount of the sun's radiation which lies inside the visible light spectrum.

Figure 8-11: Josef Stefan (1835–1893), and Ludwig Boltzmann (1844–1906)

Using the Stefan-Boltzmann formula to calculate the power radiated by the human body, at a temperature of 300 K and an external surface area of approx. 2 m2, we obtain 1 kW. This power loss could not be sustained if it were not for the compensating absorption of radiation from surrounding surfaces, at room temperatures which do not vary too drastically from the temperature of the body – or, of course, the addition of clothing.

Non-Blackbody Emitters

So far, only blackbody radiators and blackbody radiation have been discussed. However, real objects almost never comply with these laws over an extended wavelength region – although they may approach the blackbody behavior in certain spectral intervals. For example, a certain type of white paint may appear perfectly *white* in the visible light spectrum, but becomes distinctly *gray* at about 2 μ m, and beyond 3 μm it is almost *black*.

There are three processes which can occur that prevent a real object from acting like a blackbody: a fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected, and a fraction τ may be transmitted. Since all of these factors are more or less wavelength dependent, the subscript λ is used to imply the spectral dependence of their definitions. Thus:

The spectral absorptance α_λ= the ratio of the spectral radiant power absorbed by an object to that incident upon it.

The spectral reflectance ρ_λ = the ratio of the spectral radiant power reflected by an object to that incident upon it.

The spectral transmittance τ_λ = the ratio of the spectral radiant power transmitted through an object to that incident upon it.

The sum of these three factors must always add up to the whole at any wavelength, so we have the relation:

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$$

For opaque materials $\tau_\lambda = 0$ and the relation simplifies to:

$$\alpha_\lambda + \rho_\lambda = 1$$

Another factor, called the emissivity, is required to describe the fraction ε of the radiant emittance of a blackbody produced by an object at a specific temperature. Thus, we have the definition: The spectral emissivity ε_λ= the ratio of the spectral radiant power from an object to that from a blackbody at the same temperature and wavelength. Expressed mathematically, this can be written as the ratio of the spectral emittance of the object to that of a blackbody as follows:

$$\varepsilon_\lambda = \frac{W_{\lambda o}}{W_{\lambda b}}$$

Generally speaking, there are three types of radiation source, distinguished by the ways in which the spectral emittance of each varies with wavelength.

A blackbody, for which $\varepsilon\lambda = \varepsilon = 1$

A graybody, for which $\varepsilon\lambda = \varepsilon$ = constant less than 1

A selective radiator, for which ε varies with wavelength

According to Kirchhoff's law, for any material the spectral emissivity and spectral absorptance of a body are equal at any specified temperature and wavelength. That is:

$$\varepsilon_\lambda = \alpha_\lambda$$

From this we obtain, for an opaque material (since $\alpha_\lambda + \rho_\lambda = 1$):

$$\varepsilon_\lambda + \rho_\lambda = 1$$

For highly polished materials ε_λ approaches zero, so that for a perfectly reflecting material (*i.e.* a perfect mirror) we have:

$$\rho_\lambda = 1$$

For a graybody radiator, the Stefan-Boltzmann formula becomes:

$$W = \varepsilon\sigma T^4 \; [\mathrm{Watt/m^2}]$$

This states that the total emissive power of a graybody is the same as a blackbody at the same temperature reduced in proportion to the value of ε from the graybody.

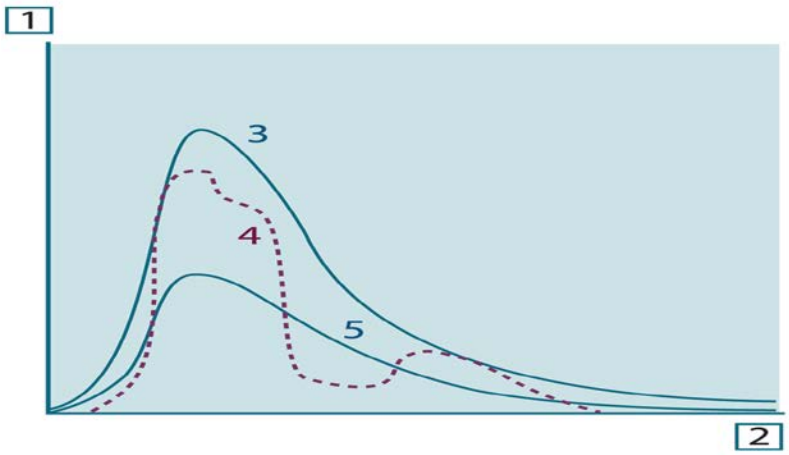


Figure 8-12: Spectral radiant emittance of three types of radiators. 1: Spectral radiant emittance; 2: avelength; 3: Blackbody; 4: Selective radiator; 5: Graybody.

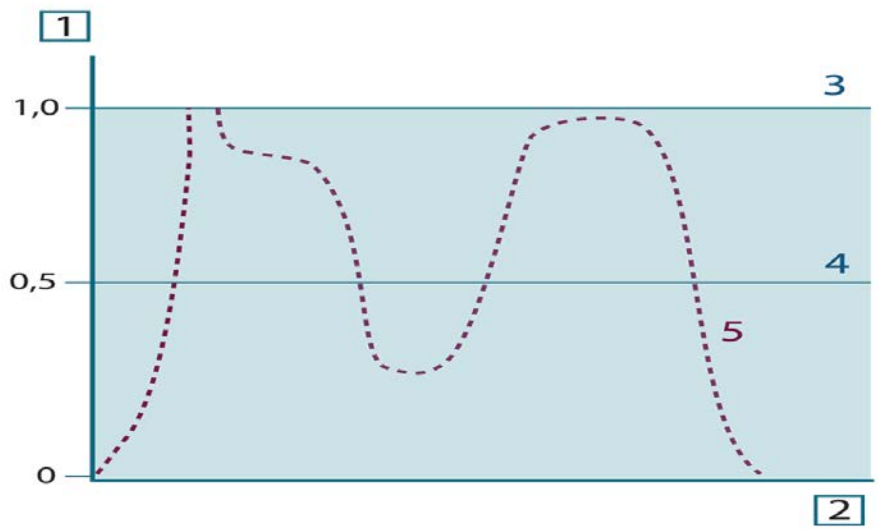


Figure 8-13: Spectral emissivity of three types of radiators. 1: Spectral emissivity; 2: Wavelength; 3: blackbody; 4: Graybody; 5: Selective radiator.

9.2.4 Infrared Semi-Transparent Materials

Consider now a non-metallic, semi-transparent body – let us say, in the form of a thick flat plate of plastic material. When the plate is heated, radiation generated within its volume must work its way toward the surfaces through the material in which it is partially absorbed. Moreover, when it arrives at the surface, some of it is reflected back into the interior. The back-reflected radiation is again partially absorbed, but some of it arrives at the other surface, through which most of it escapes; part of it is reflected back again. Although the progressive reflections become weaker and weaker they must all be added up when the total emittance of the plate is sought. When the resulting geometrical series is summed, the effective emissivity of a semi-transparent plate is obtained as:

$$\varepsilon_\lambda = \frac{(1-\rho_\lambda)(1-\tau_\lambda)}{1-\rho_\lambda \tau_\lambda}$$

When the plate becomes opaque this formula is reduced to the single formula:

$$\varepsilon_\lambda = 1 - \rho_\lambda$$

This last relation is a particularly convenient one, because it is often easier to measure reflectance than to measure emissivity directly.

9.3 The Measurement Formula

As already mentioned, when viewing an object, the camera receives radiation not only from the object itself. It also collects radiation from the surroundings reflected via the object surface. Both these radiation contributions become attenuated to some extent by the atmosphere in the measurement path. To this comes a third radiation contribution from the atmosphere itself.

This description of the measurement situation, as illustrated in the figure below, is so far a fairly true description of the real conditions. What has been neglected could for instance be sun light scattering in the atmosphere or stray radiation from intense radiation sources outside the field of view. Such disturbances are difficult to quantify, however, in most cases they are fortunately small enough to be neglected. In case they are not negligible, the measurement configuration is likely to be such that the risk for disturbance is obvious, at least to a trained operator. It is then his responsibility to modify the measurement situation to avoid the disturbance e.g. by changing the viewing direction, shielding off intense radiation sources etc.

Accepting the description above, we can use the figure below to derive a formula for the calculation of the object temperature from the calibrated camera output.

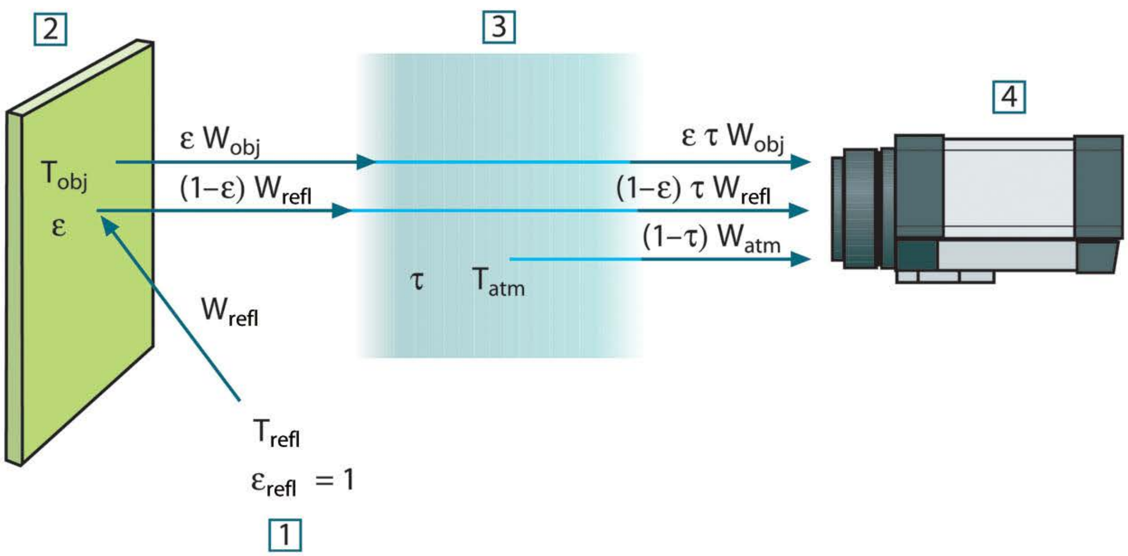


Figure 8-14: A schematic representation of the general thermographic measurement situation.1: Surroundings; 2: Object; 3: Atmosphere; 4: Camera

Assume that the received radiation power W from a blackbody source of temperature T_{source} on short distance generates a camera output signal U_{source} that is proportional to the power input (power linear camera). We can then write (Equation 1):

$$U_{source} = CW\left(T_{source}\right), \text{or with simplified notation: } U_{source} = CW_{source}$$

Where C is a constant.

Should the source be a graybody with emittance ε, the received radiation would consequently be ε W_{source}.

We are now ready to write the three collected radiation power terms:

1. Emission from the object = ετWobj, where ε is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is Tobj.
2. Reflected emission from ambient sources = (1 – ε)τWrefl, where (1 – ε) is the reflectance of the object. The ambient sources have the temperature Trefl.

It has here been assumed that the temperature T_{refl} is the same for all emitting surfaces within the halfsphere seen from a point on the object surface. This is of course sometimes a simplification of the true situation. It is, however, a necessary simplification in order to derive a workable formula, and T_{refl} can – at least theoretically – be given a value that represents an efficient temperature of a complex surrounding.

Note also that we have assumed that the emittance for the surroundings = 1. This is correct in accordance with Kirchhoff's law: All radiation impinging on the surrounding surfaces will eventually be absorbed by the same surfaces. Thus the emittance = 1.

Note

Though that the latest discussion requires the complete sphere around theobject to be considered.

3. Emission from the atmosphere = (1 – τ)τWatm, where (1 – τ) is the emittance of the atmosphere. The temperature of the atmosphere is Tatm.

The total received radiation power can now be written (Equation 2):

$$W_{tot} = \varepsilon\tau W_{obj} + (1-\varepsilon)\tau W_{refl} + (1-\tau)W_{atm}$$

We multiply each term by the constant C of Equation 1 and replace the CW products by the corresponding U according to the same equation, and get (Equation 3):

$$U_{tot} = \varepsilon\tau U_{obj} + (1-\varepsilon)\tau U_{refl} + (1-\tau)U_{atm}$$

Solve Equation 3 for U_{obj} (Equation 4):

$$U_{obj} = \frac{1}{\varepsilon\tau}U_{tot} - \frac{1-\varepsilon}{\varepsilon}U_{refl} - \frac{1-\tau}{\varepsilon\tau}U_{atm}$$

This is the general measurement formula used in all the FLIR Systems thermographic equipment. The voltages of the formula are:

Uobj = Calculated camera output voltage for a blackbody of temperature Tobj i.e. a voltage that can be directly converted into true requested object temperature.

Utot = Measured camera output voltage for the actual case.

Urefl = Theoretical camera output voltage for a blackbody of temperature Trefl according to the calibration.

Uatm = Theoretical camera output voltage for a blackbody of temperature Tatm according to the calibration.

The operator has to supply a number of parameter values for the calculation:

The object emittance ε,

The relative humidity,

Tatm

Object distance (Dobj)

The (effective) temperature of the object surroundings, or the reflected ambient temperature Trefl, and

The temperature of the atmosphere Tatm

This task could sometimes be a heavy burden for the operator since there are normally no easy ways to find accurate values of emittance and atmospheric transmittance for the actual case. The two temperatures are normally less of a problem provided the surroundings do not contain large and intense radiation sources.

A natural question in this connection is: How important is it to know the right values of these parameters? It could though be of interest to get a feeling for this problem already here by looking into some different measurement cases and compare the relative magnitudes of the three radiation terms. This will give indications about when it is important to use correct values of which parameters.

The figures below illustrates the relative magnitudes of the three radiation contributions for three different object temperatures, two emittances, and two spectral ranges: SW and LW. Remaining parameters have the following fixed values:

τ = 0.88

Trefl = +20 °C (+68 °F)

Trefl = +20 °C (+68 °F)

It is obvious that measurement of low object temperatures are more critical than measuring high temperatures since the 'disturbing' radiation sources are relatively much stronger in the first case. Should also the object emittance be low, the situation would be still more difficult.

We have finally to answer a question about the importance of being allowed to use the calibration curve above the highest calibration point, what we call extrapolation. Imagine that we in a certain case measure U_{tot} = 4.5 volts. The highest calibration point for the camera was in the order of 4.1 volts, a value unknown to the operator. Thus, even if the object happened to be a blackbody, i.e. $U_{obj} = U_{tot}$, we are actually performing extrapolation of the calibration curve when converting 4.5 volts into temperature.

Let us now assume that the object is not black, it has an emittance of 0.75, and the transmittance is 0.92. We also assume that the two second terms of Equation 4 amount to 0.5 volts together. Computation of U_{obj} by means of Equation 4 then results in U_{obj} = 4.5 / 0.75 / 0.92 – 0.5 = 6.0. This is a rather extreme extrapolation, particularly when considering that the video amplifier might limit the output to 5 volts! Note, though, that the application of the calibration curve is a theoretical procedure where no electronic or other limitations exist. We trust that if there had been no signal limitations in the camera, and if it had been calibrated far beyond 5 volts, the resulting curve would have been very much the same as our real curve extrapolated beyond 4.1 volts, provided the calibration algorithm is based on radiation physics, like the FLIR Systems algorithm. Of course there must be a limit to such extrapolations.

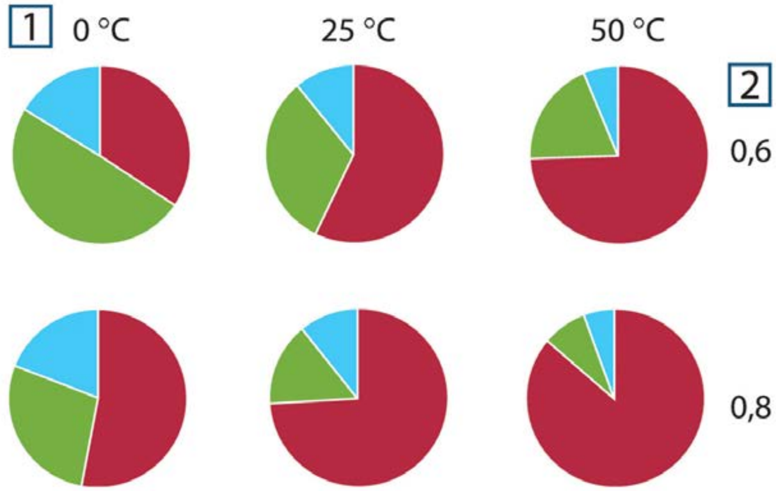


Figure 8-15: Relative magnitudes of radiation sources under varying measurement conditions (SW camera).1: Object temperature; 2: Emittance; RED: Object radiation; BLUE: Reflected radiation; GREEN: atmosphere radiation. Fixed parameters: τ = 0.88; Trefl = 20 °C (+68 °F); Tatm = 20 °C (+68 °F).

9.4 Emissivity tables

This section presents a compilation of emissivity data from the infrared literature and FLIR Systems own measurements.

Table 8-1: T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity: 6: Reference

1. Mikael A. Bramson: Infrared Radiation, A Handbook for Applications, Plenum press, N.Y.
2. William L. Wolfe, George J. Zissis: The Infrared Handbook, Office of Naval Research, Department of Navy, Washington, D.C.
3. Madding, R. P.: Thermographic Instruments and systems. Madison, Wisconsin: University of Wisconsin–Extension, Department of Engineering and Applied Science.
4. William L. Wolfe: Handbook of Military Infrared Technology, Office of Naval Research, Department of Navy, Washington, D.C.
5. Jones, Smith, Probert: External thermography of buildings..., Proc. of the Society of Photo-Optical Instrumentation Engineers, vol.110, Industrial and Civil Applications of Infrared Technology, June 1977, London.

6. Paljak, Pettersson: Thermography of Buildings, Swedish Building Research Institute, Stockholm 1972.
7. Vlcek, J: Determination of emissivity with imaging radiometers and some emissivities at l ~ 5 mm. Photogrammetric Engineering and Remote Sensing.
8. Kern: Evaluation of infrared emission of clouds and ground as measured by weather satellites, Defence Documentation Center, AD 617 417.
9. Ohman, Claes: Emittansmatningar med AGEMA E-Box. Teknisk rapport, AGEMA 1999. (Emittance measurements using AGEMA E-Box. Technical report, AGEMA 1999.)

1	2	3	4	5	6
Aluminum	anodized, black, dull	70	LW	0.95	9
Aluminum	anodized, black, dull	70	SW	0.67	9
Aluminum	anodized, light gray, dull	70	T	0.97	9
Aluminum	anodized, light gray, dull	70	T	0.61	9
Aluminum	anodized sheet	100	T	0.55	2
Aluminum	as received, plate	100	T	0.09	4
Aluminum	as received, sheet	100	T	0.09	2
Aluminum	cast, blast cleaned	70	LW	0.46	9
Aluminum	cast, blast cleaned	70	SW	0.47	9
Aluminum	dipped in HNO3, plate	100	T	0.09	4
Aluminum	Foil	27	3 µm	0.09	3
Aluminum	Foil	27	10 µm	0.04	3
Aluminum	oxidized, strongly	50-100	T	0.2-0.3	1
Aluminum	polished	50-100	T	0.04-0.06	1
Aluminum	polished, sheet	100	T	0.05	2
Aluminum	polished plate	100	T	0.05	4
Aluminum	roughened	27	3 µm	0.28	3
Aluminum	roughened	27	10 µm	0.18	3
Aluminum	rough surface	20-50	T	0.06-0.07	1
Aluminum	Sheet, 4 samples differently scratched	70	LW	0.03-0.06	9
Aluminum	Sheet, 4 samples differently scratched	70	SW	0.05-0.08	9
Aluminum	vacuum deposited	20	T	0.04	2
Aluminum	weathered, heavily	17	SW	0.83-0.94	5
Aluminum bronze		20	T	0.60	1
Aluminum hydroxide	powder		T	0.28	1
Aluminum oxide	activated, powder		T	0.46	1
Aluminum oxide	pure, powder alumina		T	0.16	1
Asbestos	Board	20	T	0.96	1
Asbestos	Fabric		T	0.78	7
Asbestos	floor tile	35	SW	0.94	1
Asbestos	Paper	40-400	T	0.93-0.95	1
Asbestos	Powder		T	0.40-0.60	1
Asbestos	Slate	20	T	0.96	8

Asphalt paving		4	LLW	0.967	1
Brass	dull, tarnished	20-350	T	0.22	9
Brass	oxidized	70	SW	0.04-0.09	9
Brass	oxidized	70	LW	0.03-0.07	2
Brass	oxidized	100	T	0.61	1
Brass	oxidized at 600 °C	200-600	T	0.59-0.61	1
Brass	polished	200	T	0.03	2
Brass	polished, highly	100	T	0.03	2
Brass	rubbed with 80- grit emery	20	T	0.20	1
Brass	Sheet, rolled	20	T	0.06	1
Brass	Sheet, worked with emery	20	T	0.2	5
Brick	Alumina	17	SW	0.68	5
Brick	common	17	SW	0.86-0.81	5
Brick	Dinas silica, glazed, rough	1100	T	0.85	1
Brick	Dinas silica, refractory	1000	T	0.66	1
Brick	Dinas silica, unglazed, rough	1000	T	0.80	1
Brick	firebrick	17	SW	0.68	5
Brick	Fireclay	20	T	0.85	1
Brick	fireclay	1000	T	0.75	1
Brick	fireclay	1200	T	0.59	1
Brick	masonry	35	SW	0.94	7
Brick	masonry, plastered	20	T	0.94	1
Brick	red, common	20	T	0.93	2
Brick	red, rough	20	T	0.88-0.93	1
Brick	refractory, corundum	1000	T	0.46	1
Brick	refractory, magnesite	1000-1300	T	0.38	1
Brick	refractory, strongly radiating	500-1000	T	0.8-0.9	1
Brick	refractory, weakly radiating	500-1000	T	0.65-0.75	1
Brick	Silica, 95 % SiO_2	1230	T	0.66	1
Brick	sillimanite, 33 % SiO_2, 64 % Al_2O_3	1500	T	0.29	1
Brick	waterproof	17	SW	0.87	5
Bronze	phosphor bronze	70	LW	0.06	9
Bronze	phosphor bronze	70	SW	0.08	9
Bronze	polished	50	T	0.1	1

Bronze	porous, rough	50-150	T	0.55	1
Bronze	Powder		T	0.76-0.80	1
Carbon	candle soot	20	T	0.95	2
Carbon	charcoal powder		T	0.96	1
Carbon	graphite, filed surface	20	T	0.98	2
Carbon	graphite powder		T	0.97	1
Carbon	lampblack	20-400	T	0.95-0.97	1
Chipboard	untreated	20	SW	0.90	6
Chromium	polished	50	T	0.10	1
Chromium	Polished	500-1000	T	0.28-0.38	1
Clay	Fired	70	T	0.91	1
Cloth	Black	20	T	0.98	1
Concrete		20	SW	0.92	2
Concrete	Dry	36	SW	0.95	7
Concrete	Rough	17	LLW	0.97	5
Concrete	Walkway	5	T	0.974	8
Copper	commercial, burnished	20	T	0.07	1
Copper	electrolytic, carefully polished	80	T	0.018	1
Copper	electrolytic, polished	-34	T	0.006	4
Copper	Molten	1100-1300	T	0.13-0.15	1
Copper	Oxidized	50	T	0.6-0.7	1
Copper	oxidized, black	27	T	0.78	4
Copper	oxidized, heavily	20	T		
Copper	oxidized to blackness		T	0.88	1
Copper	Polished	50-100	T	0.02	1
Copper	Polished	100	T	0.03	2
Copper	polished, commercial	27	T	0.03	4
Copper	polished, mechanical	22	T	0.015	4
Copper	pure, carefully prepared surface	22	T	0.008	4
Copper	Scraped	27	T	0.07	4
Copper dioxide	Powder		T	0.84	1
Copper oxide	red, powder		T	0.70	1
Ebonite			T	0.89	1
Emery	Coarse	80	T	0.85	1
Enamel		20	T	0.9	1

Enamel	Lacquer	20	T	0.85-0.95	1
Fiber board	hard, untreated	20	SW	0.85	6
Fiber board	Masonite	70	LW	0.88	9
Fiber board	Masonite	70	SW	0.75	9
Fiber board	particle board	70	LW	0.89	9
Fiber board	particle board	70	SW	0.77	9
Fiber board	porous, untreated	20	SW	0.85	6
Gold	Polished	130	T	0.018	1
Gold	polished, carefully	200-600	T	0.02-0.03	1
Gold	polished, highly	100	T	0.02	2
Granite	Polished	20	LLW	0.849	8
Granite	Rough	21	LLW	0.879	8
Granite	rough, 4 different samples	70	LW	0.77-0.87	9
Granite	rough, 4 different samples	70	SW	0.95-0.97	9
Gypsum		20	T	0.8-0.9	1
Ice: See Water			T		
Iron, cast	Casting	50	T	0.81	1
Iron, cast	Ingots	1000	T	0.95	1
Iron, cast	Liquid	1300	T	0.28	1
Iron, cast	Machined	800-1000	T	0.60-0.70	1
Iron, cast	Oxidized	38	T	0.63	4
Iron, cast	Oxidized	100	T	0.64	2
Iron, cast	Oxidized	260	T	0.66	4
Iron, cast	Oxidized	538	T	0.76	4
Iron, cast	oxidized at 600°C	200-600	T	0.64-0.78	1
Iron, cast	Polished	38	T	0.21	4
Iron, cast	Polished	40	T	0.21	2
Iron, cast	Polished	200	T	0.21	1
Iron, cast	Unworked	900-1100	T	0.87-0.95	1
Iron and steel	cold rolled	70	LW	0.09	9
Iron and steel	cold rolled	70	SW	0.20	9
Iron and steel	covered with red rust	20	T	0.61-0.85	1
Iron and steel	Electrolytic	22	T	0.05	4
Iron and steel	Electrolytic	100	T	0.05	4
Iron and steel	Electrolytic	260	T	0.07	4

Iron and steel	electrolytic, carefully polished	175-225	T	0.05-0.06	1
Iron and steel	freshly worked with emery	20	T	0.24	1
Iron and steel	ground sheet	950-1100	T	0.55-0.61	1
Iron and steel	heavily rusted sheet	20	T	0.69	2
Iron and steel	hot rolled	20	T	0.77	1
Iron and steel	hot rolled	130	T	0.60	1
Iron and steel	Oxidized	100	T	0.74	1
Iron and steel	Oxidized	100	T	0.74	4
Iron and steel	Oxidized	125-525	T	0.78-0.82	1
Iron and steel	Oxidized	200	T	0.79	2
Iron and steel	Oxidized	1227	T	0.89	4
Iron and steel	Oxidized	200-600	T	0.80	1
Iron and steel	oxidized strongly	50	T	0.88	1
Iron and steel	oxidized strongly	500	T	0.98	1
Iron and steel	Polished	100	T	0.07	2
Iron and steel	Polished	400-1000	T	0.14-0.38	1
Iron and steel	polished sheet	750-1050	T	0.52-0.56	1
Iron and steel	rolled, freshly	20	T	0.24	1
Iron and steel	rolled sheet	50	T	0.56	1
Iron and steel	rough, plane surface	50	T	0.95-0.98	1
Iron and steel	rusted, heavily	17	SW	0.96	5
Iron and steel	rusted red, sheet	22	T	0.69	4
Iron and steel	rusty, red	20	T	0.69	1
Iron and steel	shiny, etched	150	T	0.16	1
Iron and steel	Shiny oxide layer, sheet	20	T	0.82	1
Iron and steel	Wrought, carefully polished	40-250	T	0.28	1
Iron galvanized	heavily oxidized	70	LW	0.85	9
Iron galvanized	heavily oxidized	70	SW	0.64	9
Iron galvanized	Sheet	92	T	0.07	4
Iron galvanized	sheet, burnished	30	T	0.23	1
Iron galvanized	sheet, oxidized	20	T	0.28	1
Iron tinned	Sheet	24	T	0.064	4
Lacquer	3 colors sprayed on Aluminum	70	LW	0.92-0.94	9
Lacquer	3 colors sprayed on Aluminum	70	SW	0.50-0.53	9
Lacquer	Aluminum on rough surface	20	T	0.4	1

Lacquer	Bakelite	80	T	0.83	1
Lacquer	black, dull	40-100	T	0.96-0.98	1
Lacquer	black, matte	100	T	0.97	2
Lacquer	black, shiny, sprayed on iron	20	T	0.87	1
Lacquer	heat–resistant	100	T	0.92	1
Lacquer	White	40-100	T	0.8-0.95	1
Lacquer	White	100	T	0.92	2
Lead	oxidized, gray	20	T	0.28	1
Lead	oxidized, gray	22	T	0.28	4
Lead	oxidized at 200 °C	200	T	0.63	1
Lead	Shiny	250	T	0.08	1
Lead	unoxidized, polished	100	T	0.05	4
Lead red		100	T	0.93	4
Lead red, powder		100	T	0.93	1
Leather	Tanned		T	0.75-0.80	1
Lime			T	0.3-0.4	1
Magnesium		22	T	0.07	4
Magnesium		260	T	0.13	4
Magnesium		538	T	0.18	4
Magnesium	Polished	20	T	0.07	2
Magnesium powder			T	0.86	1
Molybdenum		600-1000	T	0.08-0.13	1
Molybdenum		1500-2200	T	0.19-0.26	1
Molybdenum	Filament	700-2500	T	0.1-0.3	1
Mortar		17	SW	0.87	5
Mortar	Dry	36	SW	0.94	7
Nichrome	Rolled	700	T	0.25	1
Nichrome	Sandblasted	700	T	0.70	1
Nichrome	wire, clean	50	T	0.65	1
Nichrome	wire, clean	500-1000	T	0.71-0.79	1
Nichrome	wire, oxidized	50-500	T	0.95-0.98	1
Nickel	bright matte	122	T	0.041	4
Nickel	Commercially pure, polished	100	T	0.045	1
Nickel	Commercially pure, polished	200-400	T	0.07-0.09	1

Nickel	Electrolytic	22	T	0.04	4
Nickel	Electrolytic	38	T	0.06	4
Nickel	Electrolytic	260	T	0.07	4
Nickel	Electrolytic	538	T	0.10	4
Nickel	electroplated, polished	20	T	0.05	2
Nickel	Electroplated on iron, polished	22	T	0.045	4
Nickel	electroplated on iron, unpolished	20	T	0.11-0.40	1
Nickel	electroplated on iron, unpolished	22	T	0.11	4
Nickel	Oxidized	200	T	0.37	2
Nickel	Oxidized	227	T	0.37	4
Nickel	Oxidized	1227	T	0.85	4
Nickel	oxidized at 600 °C	200-600	T	0.37-0.48	1
Nickel	Polished	122	T	0.045	4
Nickel	Wire	200-1000	T	0.1-0.2	1
Nickel oxide		500-650	T	0.52-0.59	1
Nickel oxide		1000-1250	T	0.75-0.86	1
Oil, lubricating	0.025 mm film	20	T	0.27	2
Oil, lubricating	0.050 mm film	20	T	0.46	2
Oil, lubricating	0.125 mm film	20	T	0.72	2
Oil, lubricating	film on Ni base: Ni base only	20	T	0.05	2
Oil, lubricating	thick coating	20	T	0.82	2
Paint	8 different colors and qualities	70	LW	0.92-0.94	9
Paint	8 different colors and qualities	70	SW	0.88-0.96	9
Paint	Aluminum, various ages	50-100	T	0.27-0.67	1
Paint	cadmium yellow		T	0.28-0.33	1
Paint	chrome green		T	0.65-0.70	1
Paint	cobalt blue		T	0.7-0.8	1
Paint	Oil	17	SW	0.87	5
Paint	oil, black flat	20	SW	0.94	6
Paint	oil, black gloss	20	SW	0.92	6
Paint	oil, gray flat	20	SW	0.97	6
Paint	oil, gray gloss	20	SW	0.96	6
Paint	oil, various colors	100	T	0.92-0.96	1
Paint	oil based, average of 16 colors	100	T	0.94	2

Paint	plastic, black	20	SW	0.95	6
Paint	plastic, white	20	SW	0.84	6
Paper	4 different colors	70	LW	0.92-0.94	9
Paper	4 different colors	70	SW	0.68-0.74	9
Paper	Black		T	0.90	1
Paper	black, dull		T	0.94	1
Paper	black, dull	70	LW	0.89	9
Paper	black, dull	70	SW	0.86	9
Paper	blue, dark		T	0.84	1
Paper	coated with black lacquer		T	0.93	1
Paper	Green		T	0.85	1
Paper	Red		T	0.76	1
Paper	White	20	T	0.7-0.9	1
Paper	white, 3 different glosses	70	LW	0.88-0.90	9
Paper	white, 3 different glosses	70	SW	0.76-0.78	9
Paper	white bond	20	T	0.93	2
Paper	Yellow		T	0.72	1
Plaster		17	SW	0.86	5
Plaster	plasterboard, untreated	20	SW	0.90	6
Plaster	rough coat	20	T	0.91	2
Plastic	glass fibre laminate (printed circ. board)	70	LW	0.91	9
Plastic	glass fibre laminate (printed circ. board)	70	SW	0.94	9
Plastic	Polyurethane isolation board	70	LW	0.55	9
Plastic	Polyurethane isolation board	70	SW	0.29	9
Plastic	PVC, plastic floor, dull, structured	70	LW	0.93	9
Plastic	PVC, plastic for, dull, structured	70	SW	0.94	9
Platinum		17	T	0.016	4
Platinum		22	T	0.03	4
Platinum		100	T	0.05	4
Platinum		260	T	0.06	4
Platinum		538	T	0.10	4
Platinum		1000-1500	T	0.14-0.18	1
Platinum		1094	T	0.18	4

Platinum	pure, polished	200-600	T	0.05-0.10	1
Platinum	Ribbon	900-1100	T	0.12-0.17	1
Platinum	Wire	50-200	T	0.06-0.07	1
Platinum	Wire	500-1000	T	0.10-0.16	1
Platinum	Wire	1400	T	0.18	1
Porcelain	Glazed	20		0.92	1
Porcelain	white, shiny		T	0.70-0.75	1
Rubber	Hard	20	T	0.95	1
Rubber	soft, gray, rough	20	T	0.95	1
Sand			T	0.60	1
Sand		20	T	0.90	2
Sandstone	Polished	19	LLW	0.909	8
Sandstone	Rough	19	LLW	0.935	8
Silver	Polished	100	T	0.03	2
Silver	pure, polished	200-600	T	0.02-0.03	1
Skin	Human	32	T	0.98	2
Slag	Boiler	0-100	T	0.97-0.93	1
Slag	Boiler	200-500	T	0.89-0.78	1
Slag	Boiler	600-1200	T	0.76-0.70	1
Slag	Boiler	1400-1800	T	0.69-0.67	1
Snow: See Water					
Soil	Dry	20	T	0.92	2
Soil	saturated with water	20	T	0.95	2
Stainless steel	alloy, 8 % Ni, 18 % Cr	500	T	0.35	1
Stainless steel	Rolled	700	T	0.45	1
Stainless steel	Sandblasted	700	T	0.70	1
Stainless steel	sheet, polished	70	LW	0.14	9
Stainless steel	sheet, polished	70	SW	0.18	9
Stainless steel	sheet, untreated, somewhat scratched	70	LW	0.28	9
Stainless steel	sheet, untreated, somewhat scratched	70	SW	0.30	9
Stainless steel	type 18-8, buffed	20	T	0.16	2
Stainless steel	type 18-8, oxidized at 800 °C	60	T	0.85	2
Stucco	rough, lime	10-90	T	0.91	1
Styrofoam	Insulation	37	SW	0.60	7

Tar			T	0.79-0.84	1
Tar	Paper	20	T	0.91-0.93	1
Tile	Glazed	17	SW	0.94	5
Tin	Burnished	20-50	T	0.04-0.06	1
Tin	tin–plated sheet iron	100	T	0.07	2
Titanium	Oxidized at 540 °C	200	T	0.40	1
Titanium	Oxidized at 540 °C	500	T	0.50	1
Titanium	Oxidized at 540 °C	1000	T	0.60	1
Titanium	Polished	200	T	0.15	1
Titanium	Polished	500	T	0.20	1
Titanium	Polished	1000	T	0.36	1
Tungsten		200	T	0.05	1
Tungsten		600-1000	T	0.1-0.16	1
Tungsten		1500-2200	T	0.24-0.31	1
Tungsten	Filament	3300	T	0.39	1
Varnish	Flat	20	SW	0.93	6
Varnish	on oak parquet floor	70	LW	0.90-0.93	9
Varnish	on oak parquet floor	70	SW	0.90	9
Wallpaper	slight pattern, light gray	20	SW	0.85	6
Wallpaper	slight pattern, red	20	SW	0.90	6
Water	Distilled	20	T	0.96	2
Water	frost crystals	-10	T	0.98	2
Water	ice, covered with heavy frost	0	T	0.98	1
Water	ice, smooth	-10	T	0.96	2
Water	ice, smooth	0	T	0.97	1
Water	layer >0.1 mm thick	0-100	T	0.95-0.98	1
Water	Snow		T	0.8	1
Water	Snow	-10	T	0.85	2
Wood		17	SW	0.98	5
Wood		19	LLW	0.962	8
Wood	Ground		T	0.5-0.7	1
Wood	pine, 4 different samples	70	LW	0.81-0.89	9
Wood	pine, 4 different samples	70	SW	0.67-0.75	9
Wood	Planed	20	T	0.8-0.9	1
Wood	planed oak	20	T	0.90	2

Wood	planed oak	70	LW	0.88	9
Wood	planed oak	70	SW	0.77	9
Wood	plywood, smooth, dry	36	SW	0.82	7
Wood	plywood, untreated	20	SW	0.83	6
Wood	white, damp	20	T	0.7-0.8	1
Zinc	oxidized at 400 °C	400	T	0.11	1
Zinc	oxidized surface	100-1200	T	0.50-0.60	1
Zinc	Polished	200-300	T	0.04-0.05	1
Zinc	Sheet	50	T	0.20	1