Thorlabs' 1.4 megapixel scientific CCD cameras, which offer up to 23 frames per second at 40 MHz readout of the full sensor, are specifically designed for microscopy and other demanding scientific imaging applications. These cameras are ideal for multispectral imaging, fluorescence microscopy, and other techniques that would benefit from high quantum efficiency and low noise.

**High Quantum Efficiency, Low-Noise, 1.4 Megapixel Cameras**

- High Quantum Efficiency Maximizes Signal and SNR (60% Peak Quantum Efficiency in Monochrome Versions)
- Low Read Noise Improves the Threshold of Detectability Under Low Light Conditions
- Software-Selectable 20 MHz or 40 MHz Readout: Maximize Frame Rate (40 MHz) or Minimize Noise (20 MHz)
- Asynchronous Reset, Triggered, and Bulb Exposure Modes (See Triggering Tab for Details)
- 2/3'' Format, 1392 x 1040 Monochrome or Color CCD Sensor with 6.45 μm Square Pixels (Sony ICX285AL or ICX285AQ)
- ThorCam GUI with 32- and 64-bit Windows® 7 Support
- Third-Party Software Support for LabVIEW, Matlab, μManager / ImageJ, and MetaMorph
- Full-Featured, Well-Documented API for Software Developers

Thorlabs' 1.4 megapixel scientific CCD cameras are directly compatible with our XY and Z Scanning Stages.

**Standard Package or Hermetically Sealed TE-Cooled Camera**

Our cameras are available in two package styles: a compact, non-cooled standard package and a hermetically sealed package with a two-stage thermoelectric cooler that cools the CCD. The fan-free design minimizes image blur from vibrations. Cooling the camera will reduce the dark current; however, the total dark current is also a function of exposure time. For high light levels requiring short exposure times (less than 1 second), a non-cooled camera is generally sufficient. A cooled camera is recommended for applications with low light levels requiring an exposure greater than 1 second. Please see the Camera Noise tab for more details on the various sources of camera noise and how they impact the choice between a standard and cooled camera.

**Gigabit Ethernet or Camera Link Industry-Standard Interfaces**

Thorlabs' scientific cameras are offered with a choice of Gigabit Ethernet (GiGE) or Camera Link interface. GiGE is ideal for situations where the camera must be far from the PC or there are multiple cameras that need to be controlled by the same PC. Each of these scientific cameras is provided with either a GiGE or Camera Link frame grabber card and cables, a power supply, and software; more information on what's included is on the Shipping List tab. Your computer must have a free PCI Express slot to install the GiGE or Camera Link interface. For more information on these two interface options, please see the Interface tab.

Our cameras have triggering options that enable custom timing and system control; for more details, please see the Triggering tab. External triggering requires

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1.4 Megapixel Monochrome and Color CCD Cameras

科学级摄像头，具有低读噪音

- 最高量子效率最大化信号和SNR（60% 峰值量子效率在单色版本中）
- 低读噪音提高检测阈值在低光照条件下
- 软件可选20 MHz或40 MHz读出模式：最大化帧率（40 MHz）或最小化噪声（20 MHz）
- 异步重置，触发和灯泡曝光模式（请参阅触发选项标签获取详情）
- 2/3” 格式，1392 x 1040 单色或彩色CCD传感器，6.45 μm正方形像素（Sony ICX285AL或ICX285AQ）
- ThorCam GUI，支持32-和64位Windows® 7
- 第三方软件支持LabVIEW, Matlab, μManager / ImageJ, 和MetaMorph
- 完整功能，Well-Documented API供软件开发者使用

我们的摄像头是直接兼容我们的XY和Z扫描台。

标准包或带两阶段冷凝的TE密封包

我们的摄像头有两种包装风格：一个紧凑的非冷却标准包和一个带两阶段热电致冷冷却器的带密封包，该冷却器冷却CCD。风扇免费设计可减少由于振动而引起的图像模糊。冷却相机将降低暗电流；但是，总的暗电流也是曝光时间的函数。对于高光条件，需要短曝光时间（小于1秒），非冷却相机通常足够。冷却相机推荐用于具有较低光条件的应用，要求的曝光时间大于1秒。请参阅Camera Noise标签获取各种相机噪声的更多信息以及它们如何影响标准冷却相机之间的选择。

吉比特以太网或Camera Link行业标准接口

Thorlabs的科学级摄像头提供有选择的吉比特以太网（GiGE）或Camera Link接口。GiGE适用于摄像头必须远离PC或存在多个需要由同一PC控制的摄像头的情况。每个科学级摄像头都提供有GiGE或Camera Link帧捕获卡和电缆，电源供应，和软件；有关所包含内容的更多信息请参阅Shipping List标签。您的计算机必须有一个空的PCI Express槽位来安装GiGE或Camera Link接口。有关这些两个接口选项的更多信息，请参阅Interface标签。

我们的摄像头具有触发选项，允许轻松设置时间和系统控制；对于更多详细信息，请查看触发选项标签。外部触发需要

---

1500M-CL-TE - July 13, 2016

Item # 1500M-CL-TE was discontinued on July 13, 2016. For informational purposes, this is a copy of the website content at that time and is valid only for the stated product.
a connection to the auxiliary port of the camera. Accessory cables and boards to "break out" the individual signals are available below.

Each camera comes with a user-removable IR filter; for details on the transmission please see the Specs tab. If the filter is removed, it can be replaced with a user-supplied Ø1" (Ø25 mm) filter or another optic up to 4 mm thick; please see the camera manual (found under the red Docs icon below) for details.

The cameras feature standard C-Mount (1.000"-32) threading, and Thorlabs provides a full line of thread-to-thread adapters for compatibility with other thread standards, including the SM1 (1.035"-40) threading used on our Ø1" Lens Tubes. The front face also has 4-40 tapped holes for compatibility with our 60 mm Cage System. Four 1/4"-20 tapped holes, one on each side of the housing, are compatible with our Ø1" posts. These flexible mounting options make Thorlabs' scientific cameras the ideal choice for integrating into home-built imaging systems as well as those based on commercial microscopes.

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**Monochrome Item #** | 1500M-GE | 1500M-GE-TE | 1500M-CL | 1500M-CL-TE
--- | --- | --- | --- | ---
**Color Item #** | 1501C-GE | 1501C-GE-TE | 1501C-CL | 1501C-CL-TE

| Sensor Type | Monochrome: Sony ICX285AL Monochrome CCD (Grade 0) | Color: Sony ICX285AQ Color CCD (Grade 0) |
| Effective Number of Pixels (Horizontal x Vertical) | 1392 x 1040 | |
| Imaging Area (Horizontal x Vertical) | 8.98 mm x 6.71 mm | |
| Pixel Size | 6.45 µm x 6.45 µm | |
| Optical Format | 2/3" Format (11 mm Diagonal) | |
| Peak Quantum Efficiency | Monochrome: 80% at 500 nm |
| Color: See Graph to the Right | |
| Exposure Time | 0 to 1000 seconds in 1 ms Increments | |
| CCD Pixel Clock Speed | 20 MHz or 40 MHz | |
| ADC Gain | 0 to 1023 Steps (0.036 dB/Step) | |
| Optical Black Clamp | 0 to 1023 Steps (0.25 ADU/Step) | |
| Vertical Hardware Binning | Continuous Integer Values from 1 to 24 | |
| Horizontal Software Binning | Continuous Integer Values from 1 to 24 | |
### Region of Interest
- 1 x 1 Pixel to 1392 x 1040 Pixels, Rectangular

### Read Noise
- Monochrome: <10 e- at 20 MHz
- Color: <6 e- at 20 MHz

### Digital Output
- Monochrome: 12 Bit
- Color: 14 Bit

### Cooling
- None
- -20 °C at Ambient Room Temperature

### Host PC Interface
- Gigabit Ethernet
- Camera Link

### Lens Mount
- C-Mount (1.000”-32)

- Exposure time varies with operating mode.
- ADC = Analog-to-Digital Converter
- ADU = Analog to Digital Unit
- Camera Frame Rate is impacted by the Vertical Hardware Binning parameter.
- If your application is read-noise limited, we recommend using the lower CCD pixel clock speed of 20 MHz. For more information about read noise, and for examples of how to calculate the limiting factor of total camera noise, please see the Camera Noise tab.
- For more information on these two interface options, please see the Camera Interface tab.

#### Example Frame Rates at 1 ms Exposure Time

<table>
<thead>
<tr>
<th>Sensor Size</th>
<th>20 MHz</th>
<th>40 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Sensor (1392 x 1040)</td>
<td>12 fps</td>
<td>23 fps</td>
</tr>
<tr>
<td>Full Sensor, Bin by 2 (696 x 520)</td>
<td>23 fps</td>
<td>41 fps</td>
</tr>
<tr>
<td>Full Sensor, Bin by 10 (139 x 104)</td>
<td>77 fps</td>
<td>112 fps</td>
</tr>
</tbody>
</table>

- Camera Frame Rate is impacted by the Vertical Hardware Binning parameter.

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**APPLICATIONS**

Thorlabs' Scientific-Grade CCD Cameras are ideal for a variety of applications. The photo gallery below contains images acquired with our 1.4 megapixel, 4 megapixel, 8 megapixel, and fast frame rate cameras.

To download some of these images as high-resolution, 16-bit TIFF files, please click here. It may be necessary to use an alternative image viewer to view the 16-bit files. We recommend ImageJ, which is a free download.

**Multispectral Imaging**

The video to the right is an example of a multispectral image acquisition using a liquid crystal tunable filter (LCTF) in front of a monochrome camera. With a sample slide exposed to broadband light, the LCTF passes narrow bands of light that are transmitted from the sample. The monochromatic images are captured using a monochrome scientific camera, resulting in a datacube – a stack of spectrally separated two-dimensional images which can be used for quantitative analysis, such as finding ratios or thresholds and spectral unmixing.

In the example shown, a mature capsella bursa-pastoris embryo, also known as Shepherd's-Purse, is rapidly scanned across the 420 nm - 730 nm wavelength range using Thorlabs' KURIOS-WB1 Liquid Crystal Tunable Filter. The images are captured using our 1500M-GE Scientific Camera, which is connected, with the liquid crystal filter, to a T-Scope Microscope System. The overall system magnification is 10X. The final stacked/recovered image is shown below.
Thrombosis Studies

Thrombosis is the formation of a blood clot within a blood vessel that will impede the flow of blood in the circulatory system. The videos below are from experimental studies on the large-vessel thrombosis in Mice performed by Dr. Brian Cooley at the Medical College of Wisconsin. Three lasers (532 nm, 594 nm, and 650 nm) were expanded and then focused on a microsurgical field of an exposed surgical site in an anesthetized mouse. A custom 1.4 Megapixel Camera with integrated filter wheel were attached to a Leica Microscope to capture the low-light fluorescence emitted from the surgical site. See the videos below with their associated descriptions for further information.

Arterial Thrombosis

In the video above, a gentle 30-second electrolytic injury is generated on the surface of a carotid artery in an atherogenic mouse (ApoE-null on a high-fat, “Western” diet), using a 100-micron-diameter iron wire (creating a free-radical injury). The site (arrowhead) and the vessel are imaged by time-lapse fluorescence-capture, low-light camera over 60 minutes (timer is shown in upper left corner – hours:minutes:seconds). Platelets were labeled with a green fluorophore (rhodamine 6G) and anti-fibrin antibodies with a red fluorophore (Alexa-647) and injected prior to electrolytic injury to identify the development of platelets and fibrin in the developing thrombus. Flow is from left to right; the artery is approximately 500 microns in diameter (bar at lower right, 350 microns).

Venous Thrombosis

In the video above, a gentle 30-second electrolytic injury is generated on the surface of a murine femoral vein, using a 100-micron-diameter iron wire (creating a free-radical injury). The site (arrowhead) and the vessel are imaged by time-lapse fluorescence-capture, low-light camera over 60 minutes (timer is shown in upper left corner – hours:minutes:seconds). Platelets were labeled with a green fluorophore (rhodamine 6G) and anti-fibrin antibodies with a red fluorophore (Alexa-647) and injected prior to electrolytic injury to identify the development of platelets and fibrin in the developing thrombus. Flow is from left to right; the vein is approximately 500 microns in diameter (bar at lower right, 350 microns).

Reference: Cooley BC. In vivo fluorescence imaging of large-vessel thrombosis in mice. Arterioscler Thromb Vasc Biol 31, 1351-1356, 2011. All animal studies were done under protocols approved by the Medical College of Wisconsin Institutional Animal Care and Use Committee.
BOB and TSI-IOBOB2 Break-Out Board Connector Locations

Auxiliary Connector: 6-Pin Mini Din Connector
The cameras and the break-out boards both feature female connectors, while the 1500-CAB1 cable features male connectors on both ends. Pins 1, 2, 3, 5, and 6 are each connected to the center pin of an SMA connector on the break-out boards, while pin 4 (ground) is connected to each SMA connector housing.

<table>
<thead>
<tr>
<th>Pin Number</th>
<th>Signal</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LVAL (Output)</td>
<td>Refers to “Line Valid.” It is an active-high TTL signal and is asserted during the valid period on each line. It returns low during the inter-line period between each line and during the inter-frame period between each frame.</td>
</tr>
<tr>
<td>2</td>
<td>CC1_OUT (Output)</td>
<td>An active-low TTL signal that is the buffered version of the Camera Link CC1 signal. The CC1 signal is driven from the host and is one of the software control signals for the camera. CC1_OUT allows triggering of other devices.</td>
</tr>
<tr>
<td>3</td>
<td>TRIGGER_IN (Input)</td>
<td>A TTL input used to trigger exposures on the transition from the high to low state.</td>
</tr>
<tr>
<td>4</td>
<td>GND</td>
<td>The electrical ground for the camera signals.</td>
</tr>
<tr>
<td>5</td>
<td>FVAL (Output)</td>
<td>Refers to “Frame Valid.” It is a TTL output that is high during active readout lines and returns low between frames.</td>
</tr>
<tr>
<td>6</td>
<td>STROBE (Output)</td>
<td>A TTL output that is high during the actual sensor exposure time when in continuous, overlapped exposure mode. It is typically used to synchronize an external flash lamp or other device with the camera.</td>
</tr>
</tbody>
</table>

* The same pin numbers are used on the camera and the TSI-IOBOB and TSI-IOBOB2 break-out boards.

SOFTWARE

ThorCam™

| Software | Version 2.6 |

Recommended System Requirements

- Operating System: Windows® 7 (32/64 Bit)
- Processor (CPU): ≥2.0 GHz Intel Core i5 or Core i7
- Memory (RAM): ≥8 GB
- Hard Drive: ≥500 GB (SATA)
- Graphics Card: Dedicated® Adapter with ≥256 MB RAM
- Power Supply: ≥600 W
- Motherboard: Camera Link (-CL) Cameras: One Unused PCIe x4(x8)/x8 Slot, GigE (-GE) Cameras: One Unused PCIe x1 Slot
- Connectivity: USB or Internet Connectivity for Driver Installation

- Intel Core i3 processors and mobile versions of Intel processors may not satisfy the requirements.
- On-board/integrated graphics solutions present on Intel Core i5 and i7 processors are also acceptable.
- We recommend a solid state drive (SSD) for reliable streaming to disk during image sequence storage.
ThorCam is a powerful image acquisition software package that is designed for use with our cameras on 32- and 64-bit Windows® 7 systems. This intuitive, easy-to-use graphical interface provides camera control as well as the ability to acquire and play back images. Third-party software support for packages such as LabVIEW, MATLAB, Metamorph, and µManager/ImageJ are included along with a development kit and application programming interfaces for the development of custom applications by OEMs and developers.

### Camera Control and Image Acquisition

Camera Control and Image Acquisition functions are carried out through the icons along the top of the window, highlighted in orange in the image above. Camera parameters may be set in the popup window that appears upon clicking on the Tools icon. The Snapshot button allows a single image to be acquired using the current camera settings.

The Start and Stop capture buttons begin image capture according to the camera settings, including triggered imaging.

### Timed Series and Review of Image Series

The Timed Series control, shown in Figure 1, allows time-lapse images to be recorded. Simply set the total number of images and the time delay in between captures. The output will be saved in a multi-page TIFF file in order to preserve the high-precision, unaltered image data. Controls within ThorCam allow the user to play the sequence of images or step through them frame by frame.

### Measurement and Annotation

As shown in the yellow highlighted regions in the image above, ThorCam has a number of built-in annotation and measurement functions to help analyze images after they have been acquired. Lines, rectangles, circles, and freehand shapes can be drawn on the image. Text can be entered to annotate marked locations. A measurement mode allows the user to determine the distance between points of interest.

The features in the red, green, and blue highlighted regions of the image above can be used to display information about both live and captured images.

ThorCam also features a tally counter that allows the user to mark points of interest in the image and tally the number of points marked (see Figure 2). A crosshair target that is locked to the center of the image can be enabled to provide a point of reference.

### Third-Party Applications and Support

ThorCam is bundled with support for third-party software packages such as LabVIEW, MATLAB, Metamorph, and µManager/ImageJ (see Figure 3). Both 32- and 64-bit versions of LabVIEW and MATLAB are supported. A full-featured and well-documented API, included with our cameras, makes it convenient to develop fully customized applications in an efficient manner, while also providing the ability to migrate through our product line without having to rewrite an application.
Camera Noise and Temperature

Overview

When purchasing a camera, an important consideration is whether or not the application will require a cooled sensor. Generally, most applications have high signal levels and do not require cooling. However, for certain situations, generally under low light levels where long exposures are necessary, cooling will provide a benefit. In the tutorial below, we derive the following “rule of thumb”: for exposures less than 1 second, a standard camera is generally sufficient; for exposures greater than 1 second, cooling could be beneficial; for exposures greater than 5 seconds, cooling is generally recommended; and for exposures above 10 seconds, cooling is usually required. If you have questions about which domain your application will fall, you might consider estimating the signal levels and noise sources by following the steps detailed in the tutorial below. Alternatively you can contact us, and one of our scientific camera specialists will help you decide which camera is right for you.

Sources of Noise

Noise in a camera image is the aggregate spatial and temporal variation in the measured signal, assuming constant, uniform illumination. There are several components of noise:

- **Dark Shot Noise (σ_D):** Dark current is a current that flows even when no photons are incident on the camera. It is a thermal phenomenon resulting from electrons spontaneously generated within the silicon chip (valence electrons are thermally excited into the conduction band). The variation in the amount of dark electrons collected during the exposure is the dark shot noise. It is independent of the signal level but is dependent on the temperature of the sensor as shown in Table 1.

- **Read Noise (σ_R):** This is the noise generated in producing the electronic signal. This results from the sensor design but can also be impacted by the design of the camera electronics. It is independent of signal level and temperature of the sensor, and is larger for faster CCD pixel clock rates.

- **Photon Shot Noise (σ_S):** This is the statistical noise associated with the arrival of photons at the pixel. Since photon measurement obeys Poisson statistics, the photon shot noise is dependent on the signal level measured. It is independent of sensor temperature.

- **Fixed Pattern Noise (σ_F):** This is caused by spatial non-uniformities of the pixels and is independent of signal level and temperature of the sensor. Note that fixed pattern noise will be ignored in the discussion below; this is a valid assumption for the CCD cameras sold here but may need to be included for other non-scientific-grade sensors.

Total Effective Noise

The total effective noise per pixel is the quadrature sum of each of the noise sources listed above:
**Dark Shot Noise and Sensor Temperature**

As mentioned above, the dark current is a thermal effect and can therefore be reduced by cooling the sensor. Table 1 lists typical dark current values for the Sony ICX285AL CCD sensor used in our 1.4 megapixel monochrome cameras. As the dark current results from spontaneously generated electrons, the dark current is measured by simply "counting" these electrons. Since counting electrons obeys Poisson statistics, the noise associated with the dark current $I_D$ is proportional to the square root of the number of dark electrons that accumulate during the exposure. For a given exposure, the dark shot noise, $\sigma_D$, is therefore the square root of the $I_D$ value from Table 1 (for a given sensor temperature) multiplied by the exposure time $t$ in seconds:

$$\sigma_D = \sqrt{I_D t} \tag{3}$$

Since the dark current decreases with decreasing temperature, the associated noise can be decreased by cooling the camera. For example, assuming an exposure of 5 seconds, the dark shot noise levels for the three sensor temperatures listed in the table are

$$\sigma_D(25 \, ^\circ\text{C}) = \sqrt{5 \times 5} = 5 \, \text{e}^- \tag{4}$$
$$\sigma_D(0 \, ^\circ\text{C}) = \sqrt{5 \times 1} = 2.2 \, \text{e}^-$$
$$\sigma_D(-20 \, ^\circ\text{C}) = \sqrt{5 \times 0.1} = 0.7 \, \text{e}^-$$

Figure 1, which is a plot of the dark shot noise as a function of exposure for the three temperatures listed in Table 1, illustrates how the dark shot noise increases with increasing exposure. Figure 1 also includes a plot of the upper limit of the read noise.

If the photon shot noise is significantly larger than the dark shot noise, then cooling provides a negligible benefit in terms of the noise, and our standard package cameras will work well.

**Photon Shot Noise**

If $S$ is the number of "signal" electrons generated when a photon flux of $N$ photons/second is incident on each pixel of a sensor with a quantum efficiency $QE$ and an exposure duration of $t$ seconds, then

$$S = (QE)Nt \tag{5}$$

From $S$, the photon shot noise, $\sigma_S$, is given by:

$$\sigma_S = \sqrt{(QE)N}t \tag{6}$$

**Example Calculations**

If we assume that there is a sufficiently high photon flux and quantum efficiency to allow for a signal $S$ of 10,000 e- to accumulate in a pixel with an exposure of 5 seconds, then the estimated shot noise, $\sigma_S$, would be the square root of 10,000, or 100 e-. The read noise is 10 e- (independent of exposure time). For an exposure of 5 seconds and sensor temperatures of 25, 0, and -25 °C, the dark shot noise is given in equation (4). The effective noise is:

$$\sigma_{eff} = \sqrt{\sigma_D^2 + \sigma_R^2 + \sigma_S^2}$$

$$\sigma_{eff}(25 \, ^\circ\text{C}) = \sqrt{5^2 + 10^2 + 100^2} = 100.6 \, \text{e}^- \tag{7}$$
The signal-to-noise ratio (SNR) is a useful figure of merit for image quality and is estimated as:

$$SNR = \frac{S}{\sigma_{eff}}$$  \hspace{1cm} (8)

From Equation 7, the SNR values for the three sensor temperatures are:

$$SNR(25 \degree C) = \frac{10000}{100.6} = 99.4$$  \hspace{1cm} (9)

$$SNR(0 \degree C, -20 \degree C) = \frac{10000}{100.5} = 99.5$$

As the example shows, there is a negligible benefit to using a cooled camera compared to a non-cooled camera operating at room temperature, and the photon shot noise is the dominant noise source in this example. In this case our standard package cameras should therefore work quite well.

However, if the light levels were lower such that a 100 second exposure was required to achieve 900 e- per pixel, then the shot noise would be 30 e-. The estimated dark shot noise would be 22.4 e- at 25 \degree C, while at -20 \degree C the dark shot noise would be 3.2 e-. The total effective noise would be

$$\sigma_{eff}(25 \degree C) = \sqrt{22.4^2 + 10^2 + 30^2} = 38.7 \text{ e-}$$  \hspace{1cm} (10)

$$\sigma_{eff}(-20 \degree C) = \sqrt{3.2^2 + 10^2 + 30^2} = 31.8 \text{ e-}$$

From Equation 8, the SNR values are

$$SNR(25 \degree C) = \frac{900}{38.7} = 23.3$$  \hspace{1cm} (11)

$$SNR(-20 \degree C) = \frac{900}{31.8} = 28.3$$

In this example, the dark shot noise is a more significant contributor to the total noise for the 25 \degree C sensor than for the -25 \degree C sensor. Depending on the application's noise budget, a cooled camera may be beneficial.

Figure 2 shows plots of the different noise components, including dark shot noise at three sensor temperatures, as a function of exposure time for three photon fluxes. The plots show that dark shot noise is not a significant contributor to total noise except for low signal (and consequently long exposure) situations. While the photon flux levels used for the calculations are given in the figure, it is not necessary to know the exact photon flux level for your application. Figure 2 suggests a general metric based on exposure time that can be used to determine whether a cooled camera is required if the exposure time can be estimated, and these results are summarized in Table 2. If you find that your dominant source of noise is due to the read noise, then we recommend running the camera at a lower CCD pixel clock rate of 20 MHz, since that will offer a lower read noise.

**Figure 2:** Noise from all sources as a function of exposure for three different photon fluxes: (a) low, (b) medium, and (c) high. In (c) the signal and photon shot noise saturate above approximately 20 seconds because the pixel becomes saturated at the corresponding incident photon levels. A quantum efficiency of 60% was used for the calculations. Note that these plots use logarithmic scales for both axes.

**Table 2:** From the results shown in Figure 1, these are the general “rule of thumb” recommendations related to cooling considerations based on the exposure requirements of an application. Please keep in mind that some applications are more sensitive to noise than others.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Camera Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1 s</td>
<td>Standard Non-Cooled Camera Generally Sufficient</td>
</tr>
<tr>
<td>1 s to 5 s</td>
<td>Cooled Camera Could Be Helpful</td>
</tr>
<tr>
<td>5 s to 10 s</td>
<td>Cooled Camera Recommended</td>
</tr>
<tr>
<td>&gt;10 s</td>
<td>Cooled Camera Usually Required</td>
</tr>
</tbody>
</table>

**Other Considerations**

Thermoelectric cooling should also be considered for long exposures even where the dark shot noise is not a significant contributor to total noise because cooling also helps to reduce the effects of hot pixels. Hot pixels cause a “star field” pattern that appears under long exposures. Figure 3 shows an example of this star field pattern for images taken using cameras with and without TEC cooling with an exposure of 10 seconds.
Figure 3: Images of the "star field" pattern that results from hot pixels using our (a) standard non-cooled camera and (b) our camera cooled to -20 °C. Both images were taken with an exposure of 10 seconds and with a gain of 32 dB (to make the hot pixels more visible). Please note that in order to show the pattern the images displayed here were cropped from the full-resolution 16 bit images. The full size 16 bit images may be downloaded here and viewed with software such as ImageJ, which is a free download.

**Gigabit Ethernet**

GigE is ideal for situations requiring longer cable lengths, as well as for systems that require using multiple cameras with one computer. GigE supports a speed up to 100 MB/s and cable lengths up to 100 m. It also uses fairly inexpensive cables, but does require the use of a computer with a GigE card installed. Support for multiple cameras is easily achieved using a Gigabit Ethernet switch. However, the GigE card supplied with the camera is recognized as a public connection to the network; institutions with strict policies only allow registered devices and trusted connections. For any questions regarding using our GigE card at your institution, please contact your IT department.

**Camera Link**

Camera Link is ideal for applications requiring cameras with a very high data transfer rates of up to 850 MB/s. However, the maximum cable length is 10 m. Camera Link requires the use of the supplied Camera Link card and cables for connecting to a computer, which makes it difficult to connect more than one camera to a single computer. To operate our 4 and 8 megapixel cameras in quad-tap mode a Camera Link interface is required.

**Scientific Camera Interface Summary**

<table>
<thead>
<tr>
<th>Interface</th>
<th>Gigabit Ethernet</th>
<th>Camera Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface Image</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Maximum Cable Length</td>
<td>100 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Maximum Bandwidth</td>
<td>100 MB/s</td>
<td>850 MB/s</td>
</tr>
<tr>
<td>Support for Multiple Cameras</td>
<td>Via Switch Topology</td>
<td>Typically One Camera per Camera Link Card</td>
</tr>
<tr>
<td>Available Cameras</td>
<td>200 Frames per Second Scientific-Grade CCD Cameras</td>
<td>4 Megapixel Scientific-Grade CCD Cameras</td>
</tr>
</tbody>
</table>

**Triggering**

Triggered Camera Operation

Our scientific cameras have three externally triggered operating modes: streaming overlapped exposure, asynchronous triggered acquisition, and bulb exposure driven by an externally generated trigger pulse. The trigger modes operate independently of the readout (e.g., 20 or 40 MHz; binning) settings as well as gain and offset. Figures 1 through 3 show the timing diagrams for these trigger modes, assuming an active low external TTL trigger.
External triggering enables these cameras to be easily integrated into systems that require the camera to be synchronized to external events. The Strobe Output goes high to indicate exposure; the strobe signal may be used in designing a system to synchronize external devices to the camera exposure. External triggering requires a connection to the auxiliary port of the camera. We offer the 1500-CAB1 auxiliary cable as an optional accessory. Two options are provided to "break out" individual signals. The TSI-IOBOB provides SMA connectors for each individual signal. Alternately, the TSI-IOBOB2 also provides the SMA connectors with the added functionality of a shield for Arduino boards that allows control of other peripheral equipment. More details on these three optional accessories are provided below.

Trigger settings are adjusted using the ThorCam software. Figure 4 shows the Camera Settings window, with the trigger settings highlighted with red and blue squares. Settings can be adjusted as follows:

- "HW Trigger" (Red Highlight) Set to "None": The camera will simply acquire the number of frames in the "Frames per Trigger" box when the capture button is pressed in ThorCam.
- "HW Trigger" Set to "Standard": There are Two Possible Scenarios:
  - "Frames per Trigger" (Blue Highlight) Set to Zero or >1: The camera will operate in streaming overlapped exposure mode (Figure 1).
  - "Frames per Trigger" Set to 1: Then the camera will operate in asynchronous triggered acquisition mode (Figure 2).
- "HW Trigger" Set to "Bulb (PDX) Mode": The camera will operate in bulb exposure mode, also known as Pulse Driven Exposure (PDX) mode (Figure 3).

In addition, the polarity of the trigger can be set to "On High" (exposure begins on the rising edge) or "On Low" (exposure begins on the falling edge) in the "HW Trigger Polarity" box (highlighted in red in Figure 4).

**Example Camera Triggering Configuration using Scientific Camera Accessories**

As an example of how camera triggering can be integrated into system control is shown in Figure 5. In the schematic, the camera is connected to the TSI-IOBOB2 break-out board / shield for Arduino using a 1500-CAB1 cable. The pins on the shield can be used to deliver signals to simultaneously control other peripheral devices, such as light sources, shutters, or motion control devices. Once the control program is written to the Arduino board, the USB connection to the host PC can be removed, allowing for a stand-alone system control platform; alternately, the USB connection can be left in place to allow for two-way communication between the Arduino and the PC. Configuring the external trigger mode is done using ThorCam as described above.

**Monochrome 1.4 Megapixel Scientific CCD Cameras**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>Price</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500M-GE</td>
<td>1.4 Megapixel Monochrome Scientific CCD Camera, Standard Package, GigE Interface</td>
<td>$5,100.00</td>
<td>Today</td>
</tr>
<tr>
<td>1500M-GE-TE</td>
<td>1.4 Megapixel Monochrome Scientific CCD Camera, Hermetically Sealed Cooled Package, GigE Interface</td>
<td>$8,100.00</td>
<td>Today</td>
</tr>
<tr>
<td>1500M-CL</td>
<td>1.4 Megapixel Monochrome Scientific CCD Camera, Standard Package, Camera Link Interface</td>
<td>$7,000.00</td>
<td>Lead Time</td>
</tr>
<tr>
<td>1500M-CL-TE</td>
<td>1.4 Megapixel Monochrome Scientific CCD Camera, Hermetically Sealed Cooled Package, Camera Link Interface</td>
<td>$10,000.00</td>
<td>Lead Time</td>
</tr>
</tbody>
</table>

**Color 1.4 Megapixel Scientific CCD Cameras**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>Price</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1501C-GE</td>
<td>1.4 Megapixel Color Scientific CCD Camera, Standard Package, GigE Interface</td>
<td>$5,800.00</td>
<td>Today</td>
</tr>
<tr>
<td>1501C-GE-TE</td>
<td>1.4 Megapixel Color Scientific CCD Camera, Hermetically Sealed Cooled Package, GigE Interface</td>
<td>$8,800.00</td>
<td>Lead Time</td>
</tr>
<tr>
<td>1501C-CL</td>
<td>1.4 Megapixel Color Scientific CCD Camera, Standard Package, Camera Link Interface</td>
<td>$7,700.00</td>
<td>Today</td>
</tr>
<tr>
<td>1501C-CL-TE</td>
<td>1.4 Megapixel Color Scientific CCD Camera, Hermetically Sealed Cooled Package, Camera Link Interface</td>
<td>$10,700.00</td>
<td>Lead Time</td>
</tr>
</tbody>
</table>
These optional accessories allow for easy use of the auxiliary port of the scientific camera. These items should be considered when it is necessary to externally trigger the camera, to monitor camera performance with an oscilloscope, or for simultaneous control of the camera with other devices. Additional details about the cameras’ triggering modes can be found on the Triggered Operation tab above.

**Auxiliary I/O Cable (1500-CAB1)**
The 1500-CAB1 is a 10’ (3 m) long cable that mates with the auxiliary connector on our 1.4 megapixel CCD cameras featured above and provides the ability to externally trigger the camera as well as monitor status output signals. Both ends of the cable feature a male 6-pin Mini Din connector. This cable is ideal for use with our interconnect break-out boards described below. For information on the pin layout, please see the Pin Diagrams tab above.

**Interconnect Break-Out Board (TSI-IOBOB)**
The TSI-IOBOB is designed to “break out” the 6-pin Mini Din auxiliary connector found on our scientific CCD cameras into five SMA connectors. The SMA connectors can then be connected using SMA cables to other devices to provide a trigger input to the camera or to monitor camera performance. A typical setup is shown in the image to the right, where a 1500M-GE camera is connected to a TSI-IOBOB using a 1500-CAB1 cable that must be purchased separately. The pin configurations are listed on the Pin Diagrams tab above.

**Interconnect Break-Out Board / Shield for Arduino (TSI-IOBOB2)**
The TSI-IOBOB2 offers the same breakout functionality of the camera signals as the TSI-IOBOB. Additionally, it functions as a shield for Arduino, by placing the TSI-IOBOB2 shield on an Arduino board supporting the Arduino Uno Rev. 3 form factor. While the camera inputs and outputs are 5 V TTL, the TSI-IOBOB2 features bi-directional logic level converters to enable compatibility with Arduino boards operating on either 5 V or 3.3 V logic. Sample programs for controlling the scientific camera are available for download from our software page, and are also described in the manual (found by clicking on the red Docs icon below). For more information on Arduino, or for information on purchasing an Arduino board, please see www.arduino.cc.

The image to the right shows a schematic of a configuration with the TSI-IOBOB2 with an Arduino board integrated into a camera imaging system. The camera is connected to the break-out board using a 1500-CAB1 cable that must be purchased separately. The pins on the shield can be used to deliver signals to simultaneously control other peripheral devices, such as light sources, shutters, or motion control devices. Once the control program is written to the Arduino board, the USB connection to the host PC can be removed, allowing for a stand-alone system control platform; alternately, the USB connection can be left in place to allow for two-way communication between the Arduino and the PC. The compact size of 2.70" x 2.10" (68.6 mm x 53.3 mm) also aids in keeping systems based on the TSI-IOBOB2 compact.

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>Price</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500-CAB1</td>
<td>I/O Cable with Ferrite Core for 1.4 Megapixel Scientific CCD Cameras</td>
<td>$30.00</td>
<td>Today</td>
</tr>
<tr>
<td>TSI-IOBOB</td>
<td>I/O Break-Out Board for Scientific CCD Cameras</td>
<td>$45.00</td>
<td>Today</td>
</tr>
<tr>
<td>TSI-IOBOB2</td>
<td>Customer Inspired I/O Break-Out Board for Scientific CCD Cameras with Shield for Arduino (Arduino Board not included)</td>
<td>$50.00</td>
<td>Today</td>
</tr>
</tbody>
</table>

Visit the 1.4 Megapixel Scientific Cameras for Microscopy page for pricing and availability information: