HIGH-SPEED CAMERA SELECTION
A guide to selecting the right high-speed imaging camera for analyzing explosive reactions.

What is a high-speed imaging camera, and when is it required?

A high-speed imaging camera is capable of recording rapid phenomena with high-frame rates, and then replaying the images captured as a slow motion movie. AXPRO uses high-speed imaging to record explosions. The resulting movies are then typically analyzed so that we may better understand the detonation phenomena and detonation physics (for measurement and prediction of velocity, pressure, fragmentation, and etc.).

How do I select a camera?

There are several parameters that must be considered when selecting a high-speed camera for your research. While, sometimes, a limited budget may affect your selection, it is important for research applications (and especially in explosive reactions) that your camera be able to maintain a high-frame rate. This, of course, affects the desired resolution, and thus a high-end system is typically needed if a certain resolution is desirable along with a specific frame rate.

1. Frame Rate

For explosions, as well as most any other high-speed camera application, the most obvious parameter to begin with is frame rate. The frames-per-second determines the length of your imaging - that is, a higher frame rate will provide a longer video. There are three factors that must be evaluated when determining the frame rate: image size, object velocity, and the time resolution. The image size has an enormous impact on the calculation of the frame rate. Larger events (events that have larger image sizes) tend to have lower frame rates than those observed at a higher magnification, because the events tend to occur for a longer period of time within the entire field of view. Capturing a shorter amount of time (within a smaller field of view) requires increasing the frame rate.
Figure 1. The image series above shows the detonation of a detonator - however only in the last four frames do we see any meaningful activity. While, we did indeed capture the detonation phenomena, we are significantly lacking data because we did not use the correct frame rate.

The object velocity is quite significant, as with a higher velocity, the image rate will need to increase in order to “break down” the event into smaller steps. Time resolution is the smallest unit of time that is needed to capture the event. A higher time resolution requires a higher frame rate. As an example, we will select a frame rate for imaging the detonation of a standard electric RDX detonator. First, we must decide the image size in meters (D) - here, we will choose 0.3 meters. This is a fairly simple parameter to decide if you have the camera and lens properly placed and set to capturing the desired subject. Next, is the subject velocity in meters per second (V). The detonation velocity of RDX is generally considered to be 8,750 m/s. Last, we need to decide how many times we wish to see the object before it moves outside our field of view (N). Let’s imagine that we would like to see 10 frames. The frame rate (F) required is then calculated using the following equation:

\[ F = \frac{VN}{D} = \frac{(8750 \times 100)}{0.3} \approx 291,667 \text{ frames per second.} \]

You may also calculate frame rate through Vision Research’s Maximum Frame Rate & Record Time Calculator: https://www.phantomhighspeed.com/Service-Support/Resources-Tools/Maximum-Frame-Record-Time-Calculator.
2. Image Resolution

The resolution is the number of pixels for a given field of view. The image resolution will influence what features in your image you are able resolve. To be precise, a higher resolution will provide a “higher-quality” image.

![Image Example]

**Figure 2.** A lower quality image, like the one above, will have poor features, and although these features can be resolved, it is preferable to have a high-quality, legible image to work with.

However, it is not possible, with all cameras, to achieve the highest resolution with the desired frame rate. In order to select a camera that will provide the appropriate frame rate and an adequate resolution, we should first identify the frame rate, and then evaluate the resolution of possible cameras. As an example, the two Vision Research cameras owned by AXPRO and their respective resolutions at approximately 291,667 fps are below:

- **Phantom v7.3** 32 x 8 pixels @ 222,222 fps
- **Phantom v711** 256 x 64 pixels @ 288,800 fps

In order to calculate the smallest feature that can be resolved, we need to divide the image width, by one-half the available pixel’s resolution.

- **Phantom v7.3** 0.0188 m/pixel or 18.8 mm/pixel
- **Phantom v711** 0.0023 m/pixel or 2.3 mm/pixel

From above, the v711 offers the highest resolution to resolve an object in the horizontal
direction (as well as in the vertical direction, although this is not calculated here). The exact application, however, depends, as a lower resolution may be acceptable. It is also important to note here that both camera resolutions are offering a long-thin aspect ratio.

If you own a Vision Research Camera, you may find the Generate a Table of all Valid Resolutions and Frame Rates for a Camera Tool, to be exceptionally useful: https://www.phantomhighspeed.com/Service-Support/Resources-Tools/Generate-Resolutions-and-Frames.

3. Exposure Time

Exposure time (often referred to as shutter speed) is the length of time that that the film (or digital sensor) inside of a camera is exposed to light. Exposure time affects the sharpness or blurriness of an image, also called motion blur. A minor amount of blurriness in an image is typically acceptable, but if there is a significant amount of motion blur the subject’s edges appear poorly defined, and without a well-defined outline it is difficult to measure and discern the subject.

![Figure 3](image)

**Figure 3.** The images above are an excellent example of a poor exposure time. There is too much light, especially in the later stages of the detonation, and we ultimately lose valuable data from over-exposure.

In order to choose the proper exposure duration, we should know or be able to estimate the velocity of the subject, the field of view, resolution, frame rate, and acceptable blur. To continue with our example:

\[ V = 8750 \text{ m} \]
The maximum exposure is $1/f = 1/288,800 = 3.46$ microseconds

To calculate blur with this exposure time:

$$\text{Blur} = V \times E = 8750 \text{m/s} \times 0.00000346 = 0.03 \text{m (30mm)}$$

This means that the object will have a blur of 30mm. However, to place this within context of the camera, we should know how many pixels the blurring creates on the image (for the most part, under 5 pixels is not significant). If the blur creates, perhaps, 50 pixels, then we should probably select a shorter exposure time in order to reduce the blur. In order to calculate the blur in the pixels, we need to find the pixel calibration:

$$\text{Pixel calibration} = \frac{\text{FOV}}{x} = \frac{0.3}{256} = 0.00117 \text{ (note that this differs in the horizontal and vertical directions)}$$

And thus:

$$\text{Blur in pixels} = \frac{\text{Blur}}{\text{Pixel calibration}} = \frac{0.03}{0.00117} = 25.64 \text{ pixels}$$

This aids us in understanding how to adjust exposure time - if our image size is reduced by a factor 3, then the blur in pixels will be magnified by a factor of 3, and so we will need to reduce the exposure time to 1/3 of its original value.

4. Light Sensitivity

High-speed imaging cameras typically have short exposure times because of their high frame rates. A shorter exposure time means that the time that light has to fall on the camera’s sensor is shorter. If we need to adjust the exposure time to minimize the motion blur, then we should expect to achieve a darker image.
It is beneficial to use an additional light source to illuminate the subject. As the exposure time is reduced, the external light required is increased. In AXPRO’s laboratory environment, the use of additional lighting is a simple and valuable option.

5. Synchronization/Delay Generator

Some cameras require a manual trigger – that is, we wait for the event to occur, and then trigger the camera system to begin capturing images. There are a variety of trigger systems that can be used. AXPRO uses a delay generator that sends a TTL pulse to the camera - when the camera receives the pulse, it begins filming. Triggering the camera this way is useful because it becomes much easier to “find” the imaging. If we were to film a detonation without a trigger, it would be impossible to find the data without hours of sifting through useless images. A camera trigger is any device can trigger a camera without us having to press the “on-camera shutter release button.” This can be broken down into two different categories: a hard trigger (switch closure, electronic, and image based) and a soft trigger (camera control software and image based). We will discuss hard triggers for our imaging purposes. A switch closure, or release cable, is a cable that can be plugged directly into the camera, and be easily manufactured from any household item with a button. Electronic triggers are typically used when it is not physically possible to press the shutter release button at the correct time (a TTL pulse is usually sent to the camera). Electronic sensor types include: light, sound, movement, temperature, and etc. Light sensors detect changes in light levels and are often used in start time lapse, high dynamic range, or automatic exposure bracketing shots when preset ambient lighting appears, or to perform lightening studies. Sound sensors use a microphone to detect sound that triggers the camera. Typical applications for sound sensors include: gun shots, explosions, crash tests, and etc. A movement/temperature sensor is designed to capture based on movement or temperature differences in the surrounding area. Very little movement or temperature change is needed to trigger the camera. Applications that use these kinds of sensing include: security cameras, hot spot or flame detection, wildlife, and etc.

Synchronization allows the electronic shutter to be precisely timed to operate in a phase with a timing signal. There are several synchronization tools, including: internal camera clock (crystal frequency oscillator), external clock source (f-sync signal from a second camera or any source that provides a TTL pulse), Inter-Range Instrumentation Group (IRIG-B) time code with or without phase shift, and video (f-sync pulses generated by video raster generator). Multiple cameras may be
6. Lens Selection

A proper lens is a significant part of an effective photographic system. There are a variety of considerations concerning lenses that must be taken into account. This includes: lens mount, focal length, aperture, field of view, depth of field, sensor size, and flange focal distance. The lens mount is a mechanical (and sometimes electrical) interface between the lens and the camera body. Focal length is the distance between the nodal plane of the lens and the point where the light wavelengths converge. The aperture (also referred to as the f-stop) is a hole in the lens through which the light travels. The aperture determines the amount of light that the camera receives, as well as angle of the wavelengths that come into focus on the image plane. The field of view, as previously mentioned, is effectively the image size. The depth of view is the portion of image that appears acceptably sharp (as apposed to softer portions of the image, which may appear as a background). The sensor size is the physical size of the active area of the imaging sensor. The flange focal distance is the distance between the front face of the front mount on the image camera and the image plane.

A shorter focal length, for example, produces images that are smaller, appear closer than they actually are, and have less detail of the subject. In contrast, a longer focal length will produce images that are larger, appear farther away, and have a great detail of the subject. Focal length also tends to affect the depth of field - as a general rule, the shorter the focal length of the lens is, the greater the depth of field is. The aperture (f-stop) also affects depth of field, as smaller apertures allow for greater depths of field. Lower f-stops (best) are available in commercial lenses in ranges of 1.2 - 1.5.

The appropriate lens will provide a sharp and accurate image of its subject, and will ultimately be determined by the types of images that are desired and the subject that needs to be captured. Price differences between lenses typically reflect the differences in their speed. Fast lenses, which are more expensive, admit more light and allow us to shoot in low-light conditions and at faster shutter speeds.

Vision Research offers a useful calculator that will help you to select the correct lens for a
7. Monochrome versus Polychrome

Choosing between monochrome and color systems is an important decision, depending on the application. Polychrome systems have a color mask on the sensor, which reduces sensitivity by 2 to 3 times. A polychrome system, therefore, requires 2 to 3 times more light for the image to achieve the same exposure as a monochrome system. While it may be beneficial to be able to distinguish colors for some applications, in laboratory research it is not always necessary, as the disadvantage of a reduced light sensitivity is often significant.

8. Scale

Determining a precise and accurate scale of your image size is a crucial part of experimental high-speed imaging. While sometimes this maybe as simple as placing a scale behind or next to the subject of interest, occasionally some high-speed imaging methods, such as Schieren photography, requires the use of mirrors. In this case, the scale values need to be adjusted to show the true distances.

Figure 4. An example Schlieren imaging camera set-up.

As an example, we can calculate scale from the set-up above using the following equations:

\[ D_1 + D_2 = D_{\text{total}} \]
\[ D_1 + D_2 - D_3 = D_{\text{important}} \]

\[
\frac{D_{\text{important}}}{D_{\text{total}}} = \text{Scale}
\]
This scale value can then be multiplied by the measured distances (on the image) to find the true scale.

9. Downloading

Most cameras will have an interface that we can use on our computers - this interface is what allows us to control or download images from the camera. There are a number of camera interface methods available, including: PCI, ethernet, optical, and others that are typically provided by the camera manufacturers.

Most important, perhaps, is that we are aware of how the camera saves our images. Some cameras, like the SIM X16, will “cut” the imagery before we download it onto our computer, and others, like the Phantom v.711 or the FASTCAM SA-X2, will require that we manually “cut” the images before we download them onto our computers.

10. Analysis Software

There are a number of softwares available for the analysis of your images. In general, high-speed camera manufacturers, Vision Research, for example, offer their own analysis software packages for purchase. These software can be used to edit the images/video, and also to find quantitative values, such as the velocity of the subject. There are also some image analysis programs that are available without purchase that should be considered. AXPRO typically uses ImageJ to analyze the velocities of detonation in it’s movies.

11. Results and Documentation

Finally, perhaps most important in operating a high-speed camera for research purposes, is to ensure that all settings and parameters are documented. While, you may have an excellent high-speed camera, high-quality lens, and powerful software, you will not be able to properly conduct an experiment if you cannot repeat results!

Bibliography


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AXPRO’S CAMERAS

The Phantom v7.3

The Phantom v7.3 is a discontinued camera that was manufactured by Vision Research. One of their most popular cameras, the v7.3 offers high-speed and high-sensitivity for more demanding applications. At 800 x 600 resolution, the v7.3 shoots up to 6,688 frames per second, and the 22-micron pixel allows for high light sensitivity. The maximum frames per second possible is 222,222 fps without turbo, and 500,000 fps with turbo.

The Phantom v711

The Phantom v711 is a megapixel Vision Research camera that is capable of taking 1,400,000 pictures per second. At a 1280 x 800 resolution (maximum resolution), the v711 will shoot up to 7,530 frames per second.
The SIM X16

The SIM X16 camera, manufactured by Specialized Imaging Inc. is a high-resolution (1360 x 1024) framing camera that offers up to 1,000,000,000 frames per second. An ultra high-speed camera, the SIM X16 is ideal for allowing users to capture the most difficult phenomena. Applications include: ballistics, combustion, nanotechnology, crack propagation, impact studies, and particle analysis, among others.

The FASTCAM SA-X2

The FASTCAM SA-X2, manufactured by Photron, provides one-megapixel resolution images at frame rates of up to 13,500 frames per second. 1,000,000 frames per second can be achieved with reduced resolution.