Application Note

Selecting Optics for InGaAs Imagers

1 Goodrich's SUI Team

Goodrich's SUI team (Sensors Unlimited, Inc.) is a leading manufacturer of Indium Gallium Arsenide (InGaAs) focal plane array technology. InGaAs cameras are used for imaging applications in the near-infrared (NIR) spectral region, at optical wavelengths between 900 and 1,700 nm. With special material, the wavelength response can be extended beyond 2,000 nm. Some examples of near-infrared imaging applications are silicon wafer inspection, detection of ice on aircraft wings, optical alignment and beam profiling of lasers, backside imaging of silicon integrated circuits, imaging of water content in process webs, and high-temperature thermal imaging. With so many different applications in the NIR, there are an equally large number of requirements for lens and illumination configuration. However, knowing a little about what kinds of lenses work with InGaAs imagers, as well as a few basic optical equations, can narrow the search for a useable optical setup and save a lot of valuable time.

2 Lens Properties for InGaAs Cameras

One challenge in selecting the appropriate lens for an InGaAs imager is selecting the correct lens material and optical coating. While mid-IR imagers operating beyond 2.5 µm typically require special lenses made from expensive materials such as germanium or silicon, InGaAs cameras can use lenses made of common optical glass. This is because most silica-based glasses are highly transparent in the near-infrared spectral region.

While it is true that most glass lenses will work with InGaAs imagers, it is not true that they all work well. Two factors are at work here: lens surface coatings and the design and materials of the lens itself.

Most commercial camera lenses have surface coatings designed to minimize reflection of visible light, and these coatings cause reduced transmission and increased ghost reflections at the longer NIR wavelengths. For this reason, lenses designed for visible light but used for NIR imaging should have as few optical surfaces and as few coating layers as possible. Paradoxically, this often means that a less expensive lens will out-perform a more expensive lens when used in the NIR band.

The second factor to be considered is the design of the lens. Camera lenses typically contain three or more separate pieces of glass; a combination of different lens materials and shapes is used to minimize various image aberrations. The optimum combination of materials and shapes to limit aberrations in one wavelength band usually does not work as well in a different wavelength band. This is particularly true of chromatic aberration, which is usually the performance-limiting factor when a lens designed for visible light is used in the NIR band with a broadband light source.

For most applications, these drawbacks are not too serious, and a standard C-mount video lens designed for visible-light imaging provides acceptable performance with InGaAs imaging arrays. However, when the maximum possible spatial resolution and image contrast are required, a lens specifically designed and anti-reflection coated for the near-infrared may be called for. Such NIR lenses are more expensive than lenses designed for visible light, but can provide substantial image quality improvement for critical applications, and are still considerably less expensive than germanium or silicon mid-IR lenses.

3 Basic Lens Calculations

To determine which lens to use for a particular application, we would normally start with the desired field of view or magnification, then select a convenient value for the object-to-lens distance or the lens-to-image distance, and finally determine the focal length required. To make these calculations, we need two equations from basic geometrical optics.

The first of these is called the lens equation:

$$\frac{1}{a}+\frac{1}{b}=\frac{1}{f}$$

Equation 1: Lens Equation

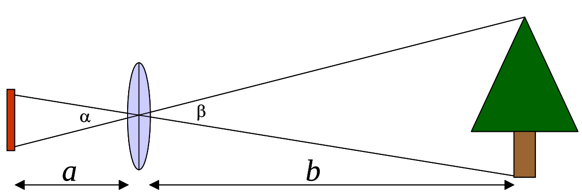

Figure 1: Lens Equation Variables

The lens equation gives the relation between the lens effective focal length (f), the distance from the object to the lens (b), and the distance from the lens to the image (a). (Note that this assumes a lens of zero thickness; this assumption will not cause significant errors so long as we keep in mind that the effective focal length f is not the same as the physical distance between the rear surface of the lens and the focal point.)

The second equation is called the magnification equation:

$$M=\frac{a}{b}.$$

Equation 2: Magnification Equation

"Magnification" is commonly defined as the ratio of the image size to the object size. The magnification equation relates this relative size to the image and object distances (a & b, respectively). In other words, this equation relates the field of view to the size of the image sensor.

What general conclusions can we draw from these two equations?

First, by taking these equations together, we have two equations in four variables (a, b, M, & f). Therefore, we are free to set any two of these four variables to whatever values we wish, then use the two equations together to determine the remaining two variables.

Second, from the lens equation only, we see that a must be equal to or greater than f: otherwise the equation would give b < 0, which is physically impossible. (We are considering only real and not virtual images here.)

Third, if the object is bigger than the image sensor, then b > a and M < 1. Except for microscopy and certain related machine vision applications, this is usually the case. Conversely, if the object is smaller than the image sensor, then a > b and M > 1. In this case we must be careful to limit b to a physically practical value, usually a few millimeters to a few centimeters.

Fourth, if b >> a, then M << 1 (i.e. the object is far away), then a ~ f and we can obtain reasonable approximations for the field of view and magnification by setting a = f. This simplifies the calculations. By the same token, if a << b then M >> 1 (i.e. the object is close), then b ~ f.

For the general case of a distant object (M << 1 and a ~ f), we can combine the two equations to express the approximate field of view as a function of the array size (d) and the object distance (b) as:

$$FOV = \frac{(d \cdot b)}{f}$$

4 Some Lens Calculation Examples

Consider the example of imaging a distant large object, as in Figure 1. Suppose we wish to view an area ten feet wide using an SUI Mini-Camera. In this case, the array is 320 pixels wide, with 40-micron pixels; this is an image width of 12.8 millimeters. Therefore, M = 12.8 mm / 10 feet ~ 1/238. Note that we have now chosen one of our two free variables. Since M << 1, a ~ f, and therefore Mb ~ f. In our example, this gives b / 238 mm = f. From this we see that we can choose either b or f arbitrarily, but not both. (We have only one of our two free parameters left.) Suppose that we are not too concerned about the value of b but wish to use the standard lens supplied with the SUI Mini-Camera. In this case we set f = 25 mm and therefore b ~ 6 meters ~ 20 feet. On the other hand, if the application requires b to be ~ 50 feet, then f = 50 feet / 238 mm, which is a lens effective focal length of approximately 65 mm.

What about resolution? In the above example, M ~ 1/238. Therefore, the area on the object that is seen by one detector pixel equals 238 times the pixel size. In our example, this is 238 x 40 µm ~ 9.5 mm. If our lens is nearly perfect, this is the minimum resolvable spot size on the object. The subject of optical resolution is complex, however, and simple computations of resolution as shown here should be considered as rough approximations.

Another common example involves imaging a small object at close range, as in microscopy or machine inspection of small objects. Suppose we need to distinguish two spots on an object that are 10 µm in diameter and located 20 µm apart. If we image these two spots onto two adjacent pixels in the image sensor, the electronic image will produce one large spot rather than two small ones with space between them. Therefore, we should image our two object spots onto at least three image sensor pixels in order to clearly distinguish them. (Optical resolution is a complex subject and this approach should be considered a rough approximation only.) If we again select the SUI Mini-Camera with 40 µm pixel spacing, then we are imaging a 20 µm distance onto an 80 µm distance (2 x 40 µm). Therefore M = 80 / 20 = 4. Since M is neither much greater nor much less than one, we cannot set b ~ f. Therefore we use M = a/b = 4 to obtain b = a/4. Substituting a/4 for b in the lens equation yields f = a/5. We could also use a = 4b to obtain f = 4b/5. Similar to the previous example, we can now select f, a, or b as the second of our two free variables and that choice will determine the value of the remaining two. If we make any one of these variables too large, the total physical length of our optical system (from object to image plane) may become impractical, since we must have a rigid and light-tight mechanical enclosure between the lens and the image. Suppose we choose a = 200 mm as the largest physically practical value for our enclosure; this gives f = 40 mm and b = 50 mm, and therefore our total system length will be approximately 250 mm. (This assumes the ideal lens of zero thickness; accounting for the exact physical length of the lens requires additional information about the lens construction that is normally not available.) A 40 mm focal length corresponds approximately to a 5X microscope objective, which is commercially available in a near-infrared design for maximum resolution or in a visible design for minimum cost.

5 Lighting Conditions and F-Stops

In considering illumination for NIR imaging, there is an important distinction between self-luminous and illuminated objects. Any object with a surface temperature greater than approximately 200°C can emit enough NIR light to yield an image under the right conditions. In this case, the object and the light source are identical. For objects near this temperature, background radiation will usually have to be controlled to obtain good images and a high-sensitivity camera used. Conversely, for objects at temperatures above 500°C, a standard camera is suitable and the emitted NIR radiation will usually swamp any background radiation. Imaging of objects at temperatures above 1,000°C typically requires reduced camera gain or the use of metallic (not “black glass” or gelatin) neutral density filters to avoid camera saturation. For example, for thermal imaging of molten metal at temperatures of the order of 1,500°C, the brightness of the object is approximately ten million times greater than that required for video-rate imaging with InGaAs. In such cases, the best solution to the saturation problem is usually to order a camera with reduced internal gain.

For “cold” objects that must be illuminated by a separate light source, many types of light sources are possible. Obviously, the source of light used with a near-infrared imager must produce sufficient near-infrared radiation to be detected by the imager. The intensity of near-infrared light emitted by a source may or may not be related to the amount of visible light it emits. For example, common fluorescent lamps emit very little near-infrared light, whereas incandescent lamps of comparable wattage emit a great deal.

As a general rule, any incandescent lamp is very bright in the near-infrared, as are other "hot" light sources such as arc or “HID” lamps. LEDs or laser diodes emitting between 0.9 and 1.7 µm also make compact, rugged, and bright NIR light sources. Sunlight is another common source of very bright near-infrared radiation, although obviously not a controllable one.

Some useful near-infrared light sources may be unexpected: the "night glow" originating in the upper atmosphere is often sufficient for outdoor near-infrared imaging in what appears to the eye to be total darkness.

As in an ordinary camera, adjusting the lens iris by one F-stop multiplies or divides the transmitted light intensity by a factor of two. Therefore, with a typical lens that is F/2 when the iris is fully open and F/16 when the iris is fully closed (a range of six F-stops), the transmitted light intensity can be adjusted over a range of 64 to one.

If you need further technical support, please contact our sales department via email sui_support@goodrich.com or call us at 609-520-0610.

About Goodrich’s SUI Team: Founded in 1991, SUI (Sensors Unlimited, Inc.) is the leading manufacturer of indium gallium arsenide (InGaAs) PIN and avalanche photodiode arrays that are used in shortwave and near infrared imaging for military, industrial, spectroscopic, machine vision, and telecommunications applications. SUI provides InGaAs photodiode array processing as a foundry service and designs custom readout integrated circuits for unique imaging applications within its ISO 9001 certified facility. For more information, visit www.oss.goodrich.com/sui.