Abstract

Splitting the optical spectrum into red, green and blue bands is necessary to reproduce images in natural color. The Philips prism was originally developed for this purpose to provide high optical efficiency, precision image alignment on a single optical axis and minimized polarization effects. The Philips configuration has since been adapted to provide other optical band combination, more channels and coverage beyond the visible. This white paper provides background on the Philips configuration, the current ranges of implementation, and the constraints on lenses and filters to be used with these prisms.

1.0 General Prism Background

A prism is a block of glass with surfaces prepared to accept or reflect light. Dozens of arrangements of these surfaces exist to redirect, rotate or otherwise manipulate the incoming light to produce a useful effect.

1.1 Index of Refraction

Since the index of refraction of glass varies with the wavelength of incident light, the effect the prism has on various wavelengths will be different. In general, the index of refraction declines with increasing wavelength in the visible, although there are exceptions. Figure 1 shows the curve for the common N-BK7 glass.

![Figure 1 – N-BK7 Index of Refraction](image-url)
When light passes through a face of a prism, its direction is changed according to Snell’s Law:

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}
\]

The top of Figure 1 is the material with the lower refractive index (air, index = 1) and the bottom is the material with the higher refractive index (glass, index 1.5 or more). Note that the velocity of the light is slowed in the medium with the higher index - \( V_2 < V_1 \) - so the effect on an image is to make the physical distance of the point of focus longer than the apparent optical distance as viewed from the low-index medium. If the two media are air and glass, then the optical distance in the glass is only about 2/3 of the physical glass length. Further, since real glass, exemplified by N-BK7, has an index that varies with wavelength, the optical distance in the glass will be different at different wavelengths. This has implications for lens design as discussed below.

### 1.2 Surface Reflections

When light passes between media with two different indexes, part of the light is reflected back from the surface. This is essentially because different indexes are equivalent to different electrical impedances and, as electrical engineers know, impedance discontinuities cause reflections. The amount of reflection for light at normal incidence is directly related to the indexes of the materials.

\[
R = \left( \frac{n_0 - n_S}{n_0 + n_S} \right)^2
\]

For air and glass (\( n_0 = 1 \) and \( n_s = 1.5 \)), the reflected amount is 4%. Note that the size of the reflection does not depend on the direction of travel of the light. The control of reflections from light leaving the prism is important because any light directed back inside the prism is bound to end up in an undesirable place. As a result, antireflection coatings at the inputs and outputs of the prism are essential.

### 1.3 Total Internal Reflection

Light traveling from air into glass can always get in regardless of its angle of arrival since rays crossing the boundary are always bent towards the normal. Even grazing rays can get in because they are bent away from the glass surface. For rays traveling out of the glass, however, the situation is different. Any ray attempting to leave at an angle closer to the surface than the angle of an arriving grazing ray will be directed back inside the glass. To this ray, the inside surface of the glass appears to be a mirror. This phenomenon is total internal reflection (TIR). TIR can produce very strong stray light patterns inside prisms and so controls on allowed direction of light travel are critical. However, TIR can also be
useful when managed properly and is essential to the operation of the Philips prism.

### 1.4 Polarization

When light reflects from the interface where the index changes, the amount of reflection depends on the angle and on the polarization of the light.

![Polarization effects on reflection](image)

This means that to avoid polarization shifts, the prism must be designed to keep entering and exiting rays near the normal and to assure that all internal reflections stay well within the TIR region. It is from these constraints that the Philips configuration emerged.

### 1.5 Beamsplitting

Placement of dichroic filters on glass surfaces allows wavelength-selective reflection and transmission. When these coatings are placed on surfaces receiving incident light, those wavelengths not wanted inside the optical system can be rejected before they enter. Absorptive filters can also be used for this purpose but those generally have less wavelength selectivity and fewer options for the shape of the transmission curve. They do have the advantage of removing the light permanently from the system rather than just redirecting it. Which technique is preferable depends on the system requirements.

When dichroic coatings are sandwiched between parallel glass surfaces, then some light can be transmitted and some reflected. When the configuration is a cube with the coating on a diagonal across two faces, the result is a 45-degree spectral beamsplitter. Because dichroic filters are built of thin layers of two materials with different indexes, careful control is required to avoid strong polarization effects form rays off the 45-degree nominal arrival angle. This makes the 45-degree beamsplitter problematic in imaging systems where the rays are generally converging. The Philips configuration relaxes this problem to some extent.
2.0 The Philips Prism

In the late 1950’s, a pair of 45-degree dichroic mirrors formed the typical color splitter for the growing number of color cameras. This configuration was large and hard to keep aligned and clean and it suffered from polarization and planarity problems. In 1960, Hendrik de Lang from Philips applied for a patent on a prism configuration that provided color separation and avoided the problems inherent in mirror assemblies. Figure 4 is figure 3 from the patent showing the form of his design that has survived until today. Originally designed for image tube cameras, this configuration was later adapted for use with CCD’s and has since been extended to additional channels. The principle, however, has remained unchanged.

2.1 Color Prism

in their canonic form, Philips prisms are used to separate an incoming image into three color (RGB) channels. The general layout of the Philips prism when used for color imaging is shown in Figure 4.
All three images are erect - that is, none of the images are inverted either top-bottom or left-right relative to the others - because the light for all channels passes either zero or two reflections.

- The optical path lengths for all three channels are identical
- The difference in S versus P polarization is minimized

In the configuration shown in Figure 5, the blue portion of the entering light is reflected from a dichroic filter and the remaining red and green (yellow) portion is transmitted. The blue light returns to the input surface where it is directed by total internal reflection to the first output. It is not necessary for this first dichroic filter to be a longpass filter between the blue and green as it is in this example. It can be either longpass or shortpass at any wavelength that the prism material will transmit.

The yellow light is split by a second dichroic filter into reflected red and transmitted green. The red light is directed to the second output by total internal reflection (this is the reason for the air gap) and the green light passes straight through to the third output. The second dichroic filter can also be either longpass or shortpass with a transition wavelength in the band transmitted by the first dichroic filter.

If the light to be imaged is narrowband or additional spectral isolation is required between channels, then trim filters can be added at the outputs for spectral shaping. In color cameras, an infrared absorbing filter is often added at the input face to assure that stray infrared never reaches the sensors.

2.2 Other Spectral Bands

The RGB configuration was designed first because the objective was true color imaging. However, the longpass and shortpass filters can have any wavelengths that fall within the spectral transmission window of the glass. Generally, using silicon detectors, the bands can be placed in the range of 350 to 1050 nm. There are some restrictions. It is not practical to make the edges of the internal filters very sharp because the effect would be smeared by the range of angles of light passing through the prism. Typically, the transition from 5% to 95% requires about 30 nm so channels spaced than 80 nm or so are not practical. Narrower bands can be presented to the sensors through the use of narrowband filters at the prism outputs but the spacing of these would still be restricted to 80 nm or so.

It is possible to use a single filter to define all narrow bands. For this purpose, a single filter with multiple passbands is placed either in front of or behind the lens to reject all but the desired narrow bands from entering the prism. This can allow some flexibility if the prism bands are relatively wide. For instance, the three bands might be 350-550 nm, 550-700 nm and 700-1050 nm. This would allow a narrow band to be selected anywhere in each of the wideband channels with a single filter.

Imaging in the near-ultraviolet can also be accommodated with the use of quartz prisms and lenses.
2.3 Neutral Splitting Layers

The splitting filters inside the prism do not necessarily all have to be spectral separators. If the first coating is a dichroic neutral splitter with a 33:67 ratio and the second coating is a neutral splitter with a 50:50 ratio, then each of the outputs will receive one-third of the incoming light. This configuration is useful when the required channel spectral bands are not known. The spectral bands can be set by putting different bandpass filters at the outputs. When the right set is identified, prisms can be built with the splitting inside to improve optical efficiency. Neutral splitters can also be used to increase scene dynamic range. The practical limit for splitters is about 10:90.

2.4 Polarization Imaging

While the prism angles are designed to minimize polarization effects, the coatings can be designed to produce particular desired polarization splits when polarization images are needed. Generally, polarizing trim filters are required in these instances to produce sufficient extinction ratios. Polarizers can also be applied to the outputs of neutral splitters with less resulting efficiency.

2.5 More or Fewer Channels

While the Philips prism was designed for use in broadcast color TV, it has many other uses, some of which require something other than three channels. Making a two-channel prism is straightforward, requiring only that a single glass block replace the second and third blocks. For four and five channel prisms, one prism is essentially stacked on top of another. The top one is a normal three-channel unit and the bottom is either a two channel or three channel unit. In either case, the straight-through channel on the bottom part simply feeds light to the top part. Figure 2 shows the configurations that result.

![Figure 2](image2.png)

Figure 6 - 2, 3, 4 and 5 channel Philips prisms

In all cases, the image sensors are positioned so that all images are erect. The coatings can be selected for the properties needed and any or all outputs can include trim filters.
2.6 Imaging at Longer Wavelengths

While most glasses are characterized only for use out to about 1000 nm, there are glasses intended for use in the 900-2300 nm short wave infrared (SWIR). These glasses can be made into prisms that accommodate bands through the visible out to the cutoff for InGaAs SWIR sensors. It is possible to mix silicon (visible/NIR) sensors and InGaAs sensors on a single prism but some alignment compromises are necessary because the pixels sizes on the silicon and InGaAs sensors will likely be different..

There is nothing to prevent prisms from being made using materials suitable for other bands out to the long wave (thermal) infrared. However, the costs of fabricating these prisms and of the multiple sensors required have so far precluded development of products.

2.7 Prism Size Determinants

To provide uniform illumination at the image plane, the prism output face must be larger than the image sensor active area. Since the rays inside a prism converge from the input to the outputs, the input face must be larger than the output faces. The actual sizes required depend, then on the imager size and the f-number of the lens. Larger sensor and lower f-numbers require larger prisms. Assuming a constant index for the prism glass of all sizes, the prism physical length and the optical path length will also increase similarly. This means that the total volume and the weight of the prism increase as the cube of the function of f-number and imager size.

Unless the lens is image-side telecentric, the practical limit to prism design is about f/2. Large sensors can be accommodated at apertures to about f/4. There exists, for instance a four-channel prism for 24 x 36 mm sensors but this is about 25 cm high and weighs nearly 10 kilograms. At the other end of the scale, a prism for three 1/3” sensors operating at f/2.8 is 14 mm high and weighs only 40 grams.

3.0 Imaging Assemblies

To make a camera, it is necessary to mount image sensors on the prism and align these relative to each other.

3.1 Sensor Mounting

Sensors may be mounted on prisms in two ways. The most compact and secure method is to glue the sensor window directly to the prism face. Due to variations in the position of the sensor inside the package, this technique usually required the incorporation of a thin layer of trim glass to move all focal planes to within ten microns of each other. The remaining variation and any rotation or tilt can then be taken up by the thickness of the glue layer during alignment. If trim filters are needed, these must be included in the glued stack. Glued sensor windows should not have AR coatings on the outside surface because this will not match the index of the glue.

This technique is needed for almost all assemblies intended for use with c-mount lenses because of the short back focal distance. However, unless the ruggedness is required, it is not recommended for use with larger or more expensive sensors since repair of glued prism assemblies is difficult and sometime impossible. One dead sensor can result in
disposal of the entire assembly.

The alternative is to mount the sensor with an air space, typically around 1 mm, between the sensor window and the prism face. In this arrangement, the sensor is usually held by a bar glued to the back of the sensor package. This bar is then attached to a frame around the prism. Often, all of these components are made of glass to provide a match for thermal expansion. Other mixed glass and metal mounts are also used. Somewhere in this assembly, provision must be made to move the sensor during alignment and secure it when alignment is achieved.

Air-space mounting allows easy sensor replacement and so is recommended for all high-value sensors. Trim filters can be added to the prism face. Both the prism face and the sensor window should be AR-coated and some sort of seal should be provided around the gap to exclude dust.

### 3.2 Stray Light Control

Generally, after assembly, the prism will be coated on the outside with black, index-matched paint to absorb any light which reaches the prism surface from the inside. Such reflections should be avoided by design but the extra precaution is useful. In addition, the black paint prevents stray light from the outside from reaching the prism. The areas around the sensors are still vulnerable to receiving stray light so camera designs should assure that the prism is operated in the dark.

Stray light can also enter through the input face so the area behind the lens should also be optically sealed and the input should be masked to limit the input area to only that which is actually covered by the lens.

### 4.0 Lenses for Prisms

While the geometry is constant for all Philips configurations, the size of the primes can vary widely depending on the sensor size and the lens f-number required. Increasing the sensor size or reducing the f-number requires bigger prisms to assure that all of the imaging rays stay inside the glass. Prisms have been made to accommodate sensors as small as 1/4" and as large as 55 x 60 mm. In all cases, optimum optical performance requires the use of lenses that include the prism glass thickness in their optical formulas. For most prisms, there is some common lens type that can focus through the glass but generally, the chromatic aberration is not as good with common lenses as with lenses designed for prism use.

Often common lenses are good enough for particular applications but users should at least examine the effects of these lenses relative to their performance requirements to decide if special or custom prism-optimized lenses are justified.

### 4.1 Ray Geometry

To work properly with prisms, lens must have relatively narrow ray angle distributions. Rays far off axis are likely to reach the walls of the prism and end up in unintended places on the image sensor. In addition, since the internal filters are dichroic, their transmission
curves depend on the angle of the arriving rays. The transmission curve of a dichroic filter shifts towards the longer wavelengths for rays farther and farther off-normal. A good example of this is television broadcast, which uses almost exclusively lenses that incorporate of image-side telecentricity to minimize color shading from ray angle variations across the image.

Since prisms appear optically shorter than their physical length, the use of a prism can create mechanical clearance to permit use of optics that seem unlikely to fit in the available space. This is why c-mount optics can often be used with sensor up to 1/3” in size even though the prisms needed to accommodate the image size are thicker than the back focal length of the lenses.

4.2 Infrared Imaging

Operating outside the visible will usually require a custom lens design. A small number of lenses corrected for the 400-1000 nm visible/NIR band are available for use with sensors up to 2/3” and for prisms up to five channels. There is continuing development in this area as the application of prism cameras expands into industrial and agricultural uses.

However, as of this writing, there are no existing SWIR lenses that include the prism in their optical design. This accommodation is even more important in the SWIR band than in the visible because the index of the glasses changes much more rapidly with wavelength in the range beyond 1300 nm.

Farther in the infrared, reflective optics could be applied. These have the advantage of being chromatically neutral but must be designed with the long back focal distance required to accommodate prisms. With the cost of microbolometer imagers falling, multispectral LWIR cameras may become affordable. In any event, building prisms from infrared optical materials will remain a challenge.