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POLARIZATION: THE INVISIBLE PROPERTY OF LIGHT

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Polarization: the invisible property of light

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Human sight is generally not sensitive to the polarization state of light. If you were color blind then friends would see things you don't and tell you, but with polarization no-one sees it and its existence is hidden. In many ways describing polarization is therefore like describing a sunset to a blind person.

In cockpit lighting applications, the source may be polarized e.g. AMLCD displays. The pilot does not see this polarization but any instrument used to measure the color or luminance can be affected. To ensure the instrument is suitable, MIL-L-85762A and MIL-STD-3009 recommend a specific test for luminance polarization error. Photometers failing this test cannot be used for luminance measurements.

A bit of history: Polarization was possibly used as an aid to navigation by the Vikings around 1000 years ago. This predates the use of the compass in the western world! Crystal cordierite is common in Norway and some historians believe Vikings used this naturally occurring mineral to see polarization. When the sun is low in the sky, any portion of clear sky can be used to indicate the sun's position because the scattered blue light is polarized. Even if you can't see the sun you can know where it is simply by rotating the cordierite until the sky becomes a deep blue; the deep blue forms a line across the sky at a right angle to the sun.

The scientific study of polarization did not begin until the late 17th century however. Even then, eminent scientists like Newton opposed several correct theories because he thought light could not be both a particle and a wave. Not until Thomas Young's famous double slit interference experiment in 1801 was the wave nature of light proved.

Polarization occurs widely in nature. For instance, glare from the surface of water makes it difficult to see what is beneath. A polarizing film held in one orientation seems to have no effect whereas the glare is reduced or completely eliminated if the film is rotated 90°. If reflections from the water surface are affected by the polarizer the light must be polarized. If the reflection is polarized then the transmission must be polarized too. It is not surprising to discover therefore that some aquatic animals have evolved to see and use polarization. A cuttlefish is known for its ability to change the color of its skin, but a less known fact is it can change the light polarization. Polarization can also help to see and identify prey. Ctenophore plankton is almost completely transparent in unpolarized light but when placed between crossed polarizers stands out against the background. A mixture of these images, equivalent to the partial polarization conditions under water, gives an optimum image for recognition.

So what is polarization? We know the light behaves like a wave, but what type? There are two basic types of wave, transverse and longitudinal. These are illustrated in Figure 1. Longitudinal waves occur in the same direction as the travel and include examples such as sound moving through air, sonar and other compression waves. Transverse waves occur at right angles to the direction of travel and include examples such as ripples across the surface of water or plucking a guitar string. Longitudinal waves cannot be polarized but transverse waves vibrate in a plane and hence are confined to a specific orientation. There are an infinite number of planes around the directions of travel and if the light is a random mix of planes it is called unpolarized. If all the light vibrates in the same plane it is linearly polarized, and the line is the orientation of the plane (or more precisely the orientation of the electric vector of the light).

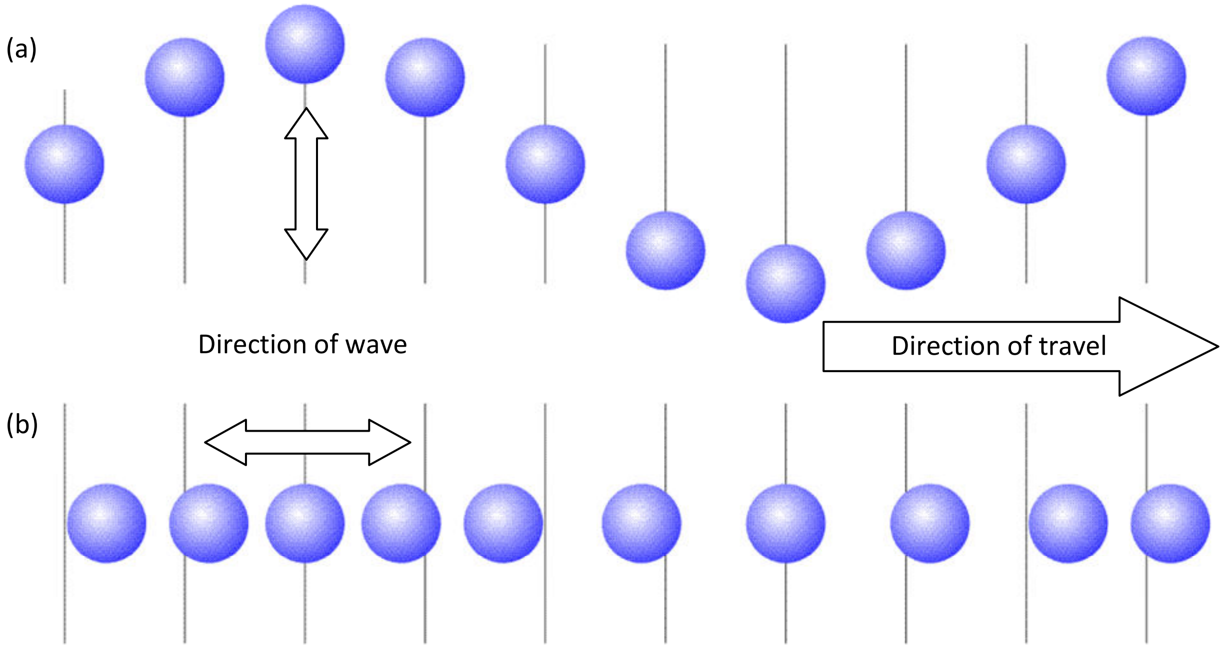

Figure 1. Wave types: (a) transverse (b) longitudinal.

Perhaps the most common form of polarizer, but not the best, is polaroid. This is found in sunglasses, displays and many applications where the highest performance is not required. It is simply a material made up of long thin molecules that are aligned in a particular orientation. Light is absorbed by chemical bonds and hence polarized light in the direction of the bonds is absorbed. Light polarized at 90° to the bonds passes through the material and therefore the emerging light is linearly polarized.

Several rules can be used for perfect polarizers to describe the behavior of polarizer combinations.

1. If unpolarized light passes through a polarizer, 50% of the light will be transmitted (ignoring absorption). This is true for all orientations of the polarizer. Light emerging will be linearly polarized according to the orientation of the polarizer.

2. A second polarizer of the same orientation will transmit all the light passed by the first one.

3. As the angle between the orientations of the two polarizers is increased, the intensity transmitted decreases. It varies with the square of the cosine of the angle. This is called Malus' law.

4. The transmittance depends only on the angle between the polarizer orientations. The order of the polarizers doesn't matter.

5. In accordance with Malus' law crossed polarizers, that is polarizers with orientations at 90˚ to each other, transmit no light ($\cos^2(90^\circ)=0$).

6. The order does matter if three or more polarizers are in series. For example, if a third polarizer is added after the cross polarizers at 45˚ to them both, none of the original unpolarized light gets through. Since polarizers do not create light this must be true. However, move the 45˚ polarizer between the crossed polarizers and now light is transmitted. It is clear from this that polarizers do not simply absorb light. Imagine the polarizer as a picket fence and the light wave as a wave in a rope extending through a gap in the fence. As the rope is moved up and down the wave gets through the fence because vertically the gap is large. Moving the rope left to right creates waves that would be blocked by the fence because horizontally the gap is small. If the direction of the wave is not quite vertical, contacts with the sides of the gap would tend to nudge the wave slightly and hence rotate the wave. Naturally, this analogy can only be taken so far but it is a useful visualization tool.

Extending this principle to a large number of polarizers, it is possible to incrementally rotate the polarization plane so as to transmit between end cross-polarizers. This makes the transmittance very dependent on the polarizer orientations and any disruption in the incremental rotations would affect observed intensity. LCD displays use this principle, controlling the alignments with applied voltage.

The more polarizers that can be incrementally arranged between the end crossed polarizers, the higher the transmittance. By aligning the two surface molecules at 90°, the natural tendency of liquid crystal molecules to align with its neighbors will result in thousands of incremental orientations, making the transmittance very efficient. The applied voltage then disrupts the alignment, reducing transmittance.

Polarization can also result from reflection. This is the glare from water discussed earlier. The incident, reflected and refracted rays are all within a plane, called the p-plane. At 90° to the p-plane is the s-

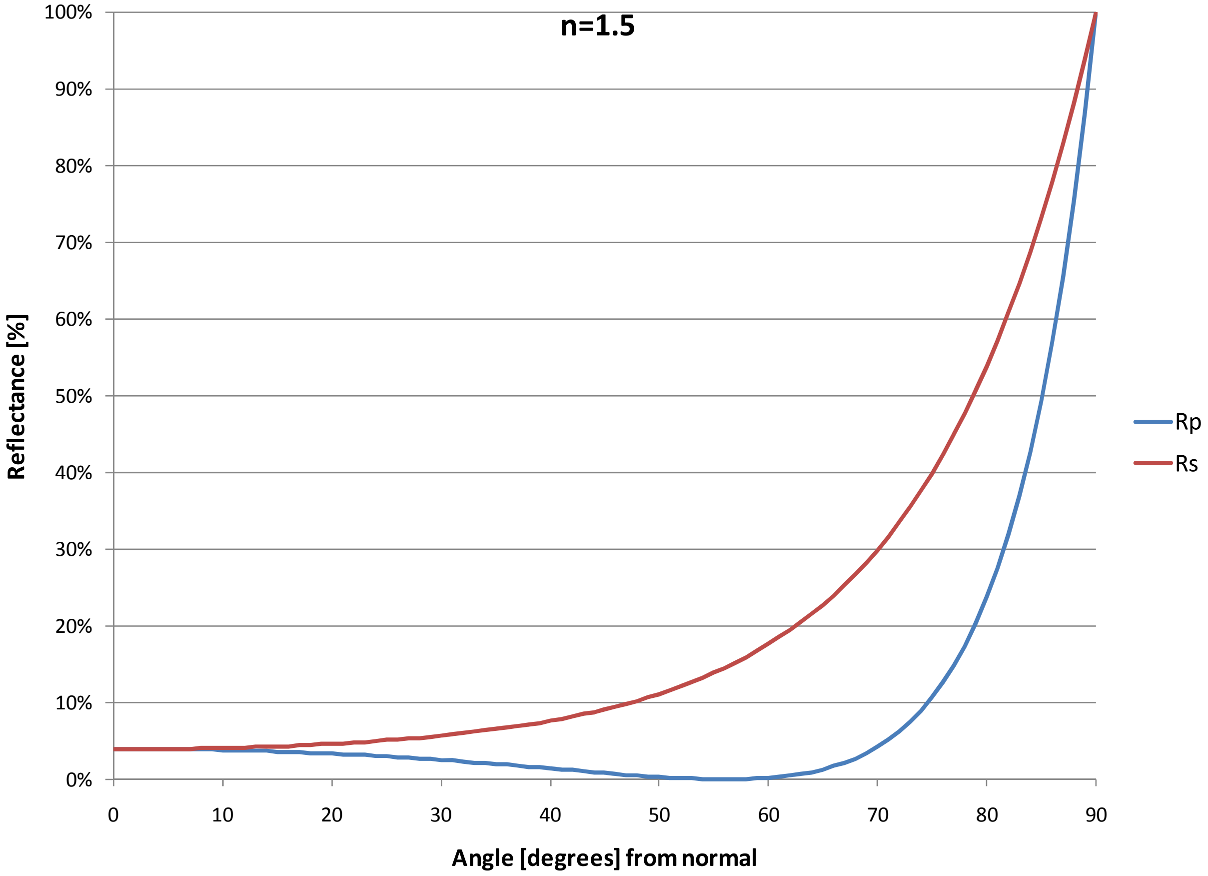

Figure 2. The reflectivity of a surface depends on the light polarization. Rp and Rs are the reflectivities in the p- and s- planes respectively.

plane. Fresnel described the reflection for these two polarizations mathematically so we can calculate the reflectance at any angle.

At most angles the two polarizations have different reflectivities. In fact, the p-polarized light decreases to zero reflectance at one angle, known as the Brewster angle. At this angle reflected light must be entirely s-polarized. Of course transmittance is partially polarized since there is now more p-polarized than s-polarized light. A stack of many parallel plates, where this effect is repeated at each surface, results in the transmitted beam being essentially p-polarized and the reflection being entirely s-polarized.

Light can interact with materials in many different ways, and polarization adds a new dimension to those interactions. For instance, some molecules rotate the plane of polarization. These molecules lack symmetry apart from mirror images and come in left-hand and right-hand opposites. The rotation seen depends on both the strength of the rotational effect and the path length of light, but each mirror image rotates light in opposite directions. This property is commonly used in the pharmaceutical industry to distinguish the two forms. This is because biological enzymes only work on one form and the other is unreactive. In fact L-amino acids (L- is short for Levo- which means left-handed) are used exclusively to build proteins by all life on earth. Molecules that have the same formula but different arrangements of atoms are called isomers. These particular isomers are so similar they can only be distinguished using polarized light and are therefore called optical isomers (or enantiomers).

If absorption within a material is polarization dependent it is dichroic. A polarizer is therefore dichroic but normally the term is reserved for materials that have highly wavelength dependent dichroism since separation of colors is the primary application of this effect.

Some materials refract polarized light in different ways. Instead of having just one index of refraction these substances have two, depending on the polarization through the crystal. This means that the different polarizations follow two distinct paths through the material; giving the phenomenon the name double refraction or birefringence. A common example is calcite, in which this phenomenon is so strong it produces double images. The double image effect can be seen clearly if the rays are traced for each polarization axis. A single image is observed if one of these polarizations is blocked with a polarizer. Since refractive index depends on the ratio of light velocities, this must mean that the ray with higher refractive index is moving slower through the material.

If the birefringent material is cut so that its thickness slows one polarization down and the emerging light is 90° out of phase to the other polarization, it is called a quarter wave plate. The resultant vector of the two polarizations will rotate and this is called circular polarization. Many effects of circular polarization are indistinguishable from random polarization (unpolarized). A quarter wave plate therefore depolarizes linearly polarized light. Variations on this can effectively convert any polarization state to any other and such devices are used in many applications.

Strain can often give materials birefringent properties. This means the polarization state of light exiting the material is no longer the same as that entering. Placed between crossed polarizers the altered light is now transmitted. Since the birefringence is wavelength dependent, different strains show up as different colors.

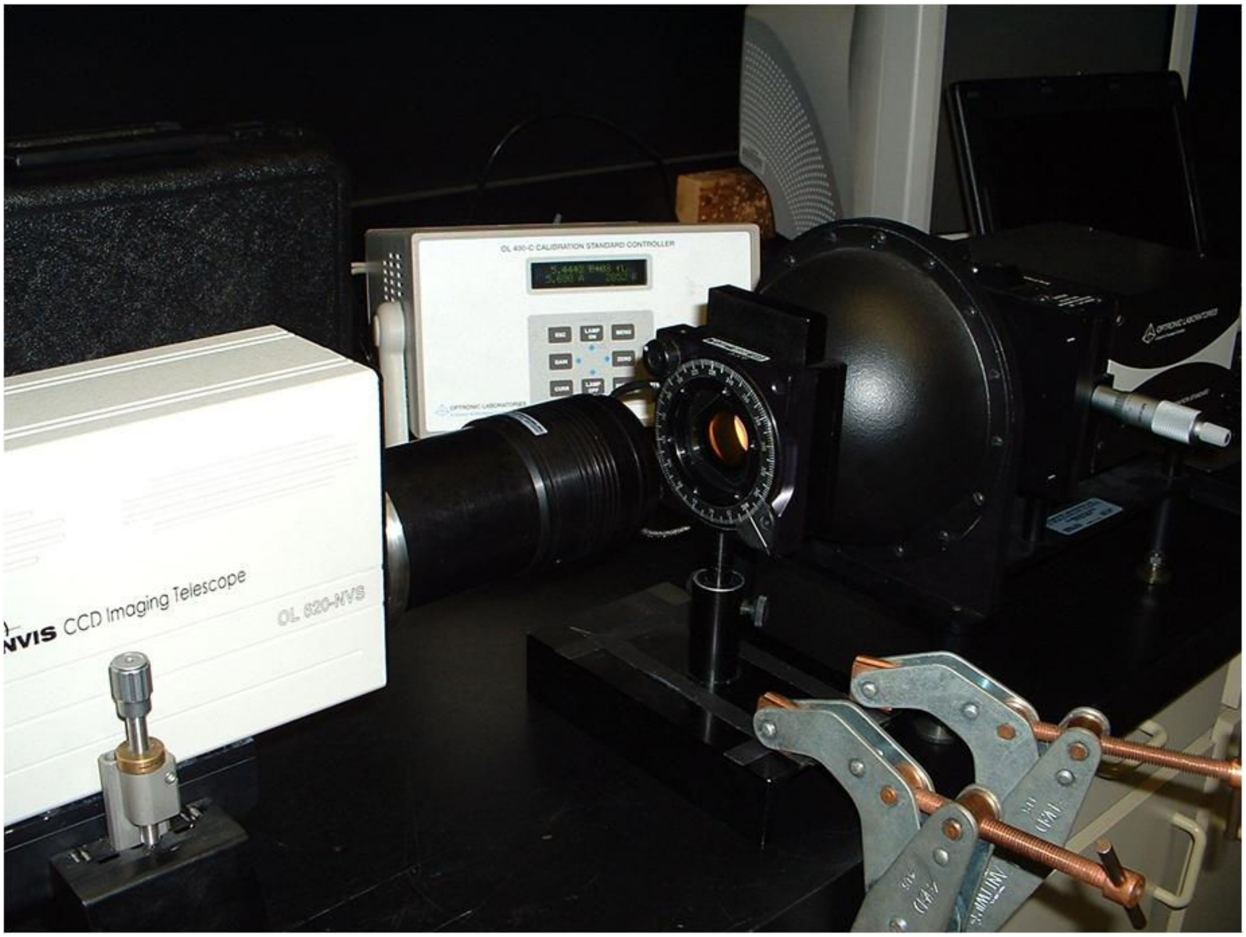

Figure 3. Setup for measuring the polarization sensitivity of a detection system.

When it comes to measuring polarization, a polarization analyzer is used. This analyzer is just a polarizer as discussed previously, but it is rotated while measuring the light with a detector. We can think of any measurement arrangement as having two polarizers, one stationary and one rotating. A polarized source behaves like an unpolarized source with a stationary polarizer in front of it, so we would map the source polarization using the analyzer plus a detector. In the same way, a detector that is sensitive to polarization acts like a polarization-insensitive detector with a stationary polarizer in front of it, and is mapped using the analyzer is used in conjunction with a source.

On a polar plot light that is 100% polarized would change from a maximum value to zero (crossed polarizer condition) and look like a double lobe. Completely unpolarized light would have the same signal at all angles and look circular. Partially polarized light would be intermediate and appear elliptical or peanut shaped depending on the plot scale.

Figure 3 is a practical setup for measuring polarization sensitivity of a detector system. The integrating sphere guarantees completely unpolarized light enters the polarization analyzer. The analyzer output

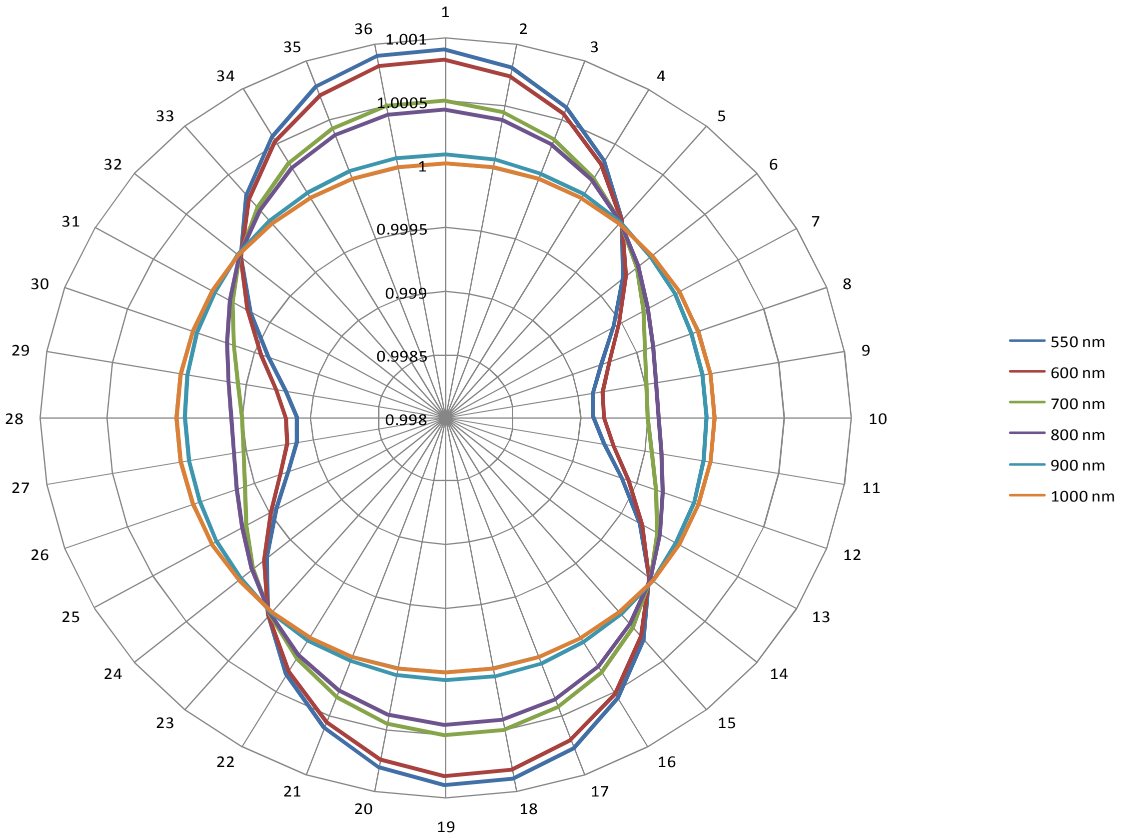

Figure 4. Results for tests on an OL 770-NVS system. The intensity is shown by the radial distance from the center and the angle is the position around the circumference. Note that all curves are within ±0.1%.

should therefore be linearly polarized but of equal intensity at all angles. Measurements of the signal at the detector (radiance or luminance in this case) are made for each angle of the analyzer.

Figure 4 is a typical measurement of a production OL 620[1] telescope coupled to an OL 770-NVS system at several wavelengths. In fact polarization sensitivity is usually wavelength dependent, with longer wavelengths being less sensitive. It should be noted that the scale is set to emphasize differences and that all curves are actually within ±0.1%. At longer wavelengths the curve is almost perfectly circular, indicating negligible polarization sensitivity. This slight polarization sensitivity is primarily due to residual strain in the lenses after grinding.

Commercial camera lenses are made to a very high quality but are more than three times worse in polarization sensitivity than the OLI lenses. Some telescope designs are much worse, giving performance more than 30 times greater polarization sensitivity than the OL 620 and failing the MIL-STD-3009 requirements (±0.5% max).

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[1] The OL 620 and OL 770-NVS are products of Optronic Laboratories, Inc. designed specifically for MIL-STD-3009 and MIL-L-85762A testing of displays (http://www.olinet.com/)

Probably the worst of all is a telescope directly coupled to monochromator. This polarization sensitivity is due to the monochromator and not the telescope. Maximum sensitivities of three times the minimum are usual, resulting in widely ranging results depending on the polarization of the source measured. In this case, a depolarizer is essential to remove the polarization error and obtain reliable results.

Returning to the MIL-STD-3009 specifications[2]:

> ***A.4.6 Photometer polarization error.***
>
> *The polarization error shall be no greater than 1%.*
>
> ***A.4.6.1 Photometer polarization error verification.***
>
> *The polarization error shall be checked by placing a linear polarizer in the optical path between the standard lamp and the photometer and then measuring the luminance. The polarizer shall be rotated 45˚ and another measurement shall be made. The polarizer shall be rotated another 45˚ and another measurement shall be made. The photometer shall be considered as having passed the polarization error test if the difference between the three measurements is lower than or equal to the percent error specified in A.4.6. Throughout the test the alignment of the standard lamp shall not be changed. The transmission of the linear polarizer shall be greater than or equal to 20%, and the transmission of two pieces of the polarizer material, when oriented so that the direction of polarization of the two pieces are at right angles, shall be less than or equal to 0.1%.*

The testing method described relies on just three measurements at 45° intervals. How does this fit with the complete rotation tests? Also, “difference between the three measurements” refers to a difference but “percent error” implies a ratio without specifying if it is a ratio of the difference to the maximum, average or other value. This ambiguity can lead to several possible interpretations of the specification. Degree of polarization is defined as **(max-min)/max** when applied to the complete rotation measurement. If we assume that the MIL specification of polarization error is attempting to define the same quantity over the three measurement angles we can calculate the relationship between the two techniques.

Taking 100% polarization to illustrate the relationship as shown in Figure 5, we can start at any angle. At -45°/0°/+45° we see that the polarization error is 50% {=(1-0.5)/1}; very different to the degree of polarization. If we measure 0°/+45°/+90° the calculated polarization error is 100% {=(1-0)/1}, agreeing with the degree of polarization. Angles of +45°/+90°/+135° also give 100% polarization error {=(0.5-0)/).5}.

If we plot the polarization error indicated by the MIL specification against the central angle (See Figure 5) we can see the value varies between 50% and 100% for all sets of measurements at three 45˚ angles. It is only 100% at 6 specific sets of angles and everywhere else the result is different to the degree of polarization.

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[2] MIL-L-85762A has the same wording but section headings of B.40.6 and B.40.6.1

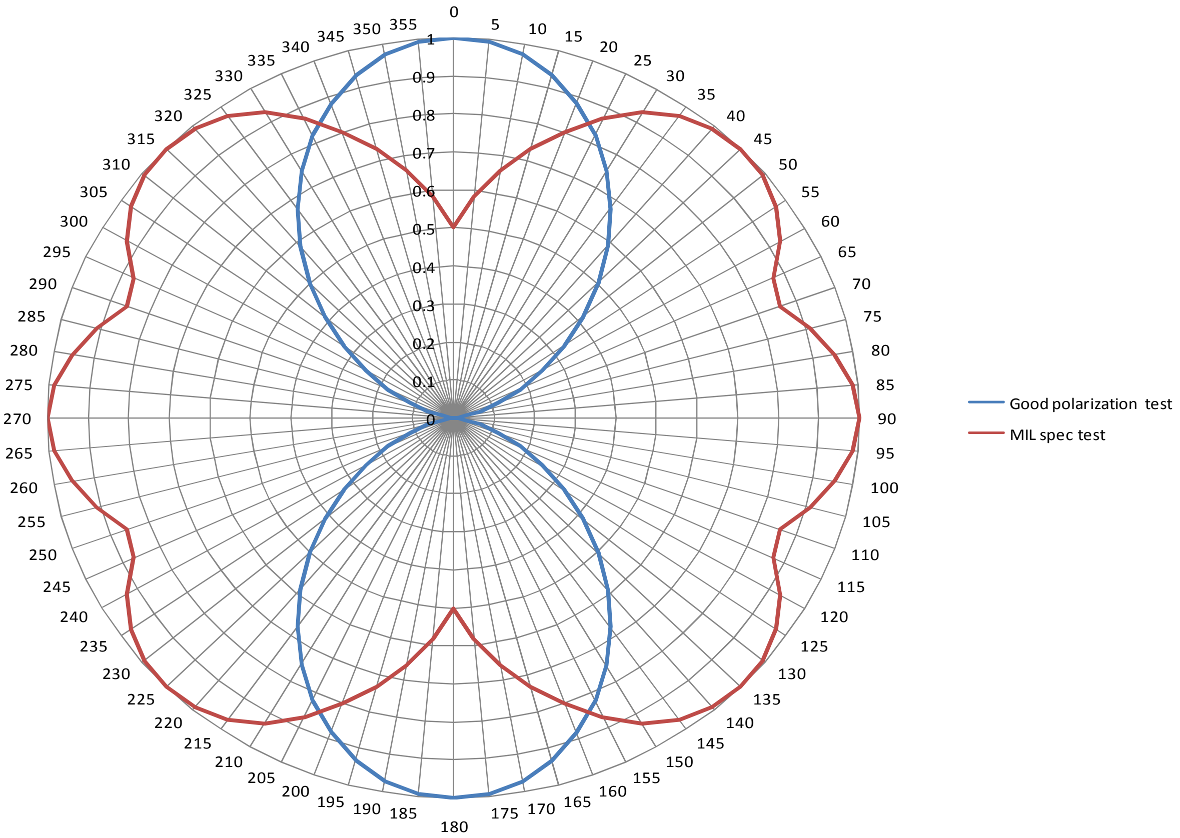

Figure 5. A polar plot of 100% polarized light with results of the MIL-STD-3009 test superimposed.

This indicates that although it is likely the authors of the standard intended some equivalence of polarization error to degree of polarization; the two are not at all equivalent. Moreover, they are only equal at the worst case angles and it is likely that some manufacturers would conduct tests at best case conditions since this makes their instruments look better.

Although the MIL specifications do not specifically require the optimal testing of polarization error, it is likely the intent was to ensure that high quality data is obtained. To conform to the spirit rather than the letter of the document manufacturers should therefore test to worst case polarization error. Also, the greatest polarization error occurs in uncorrected spectroradiometric systems whereas the MIL specification is in the photometer section. To provide correct results and performance for both luminance and color, the specification should be applied equally to spectroradiometers. If properly corrected, spectroradiometers should pass this specification easily.