Hawkeye Polarization Performance

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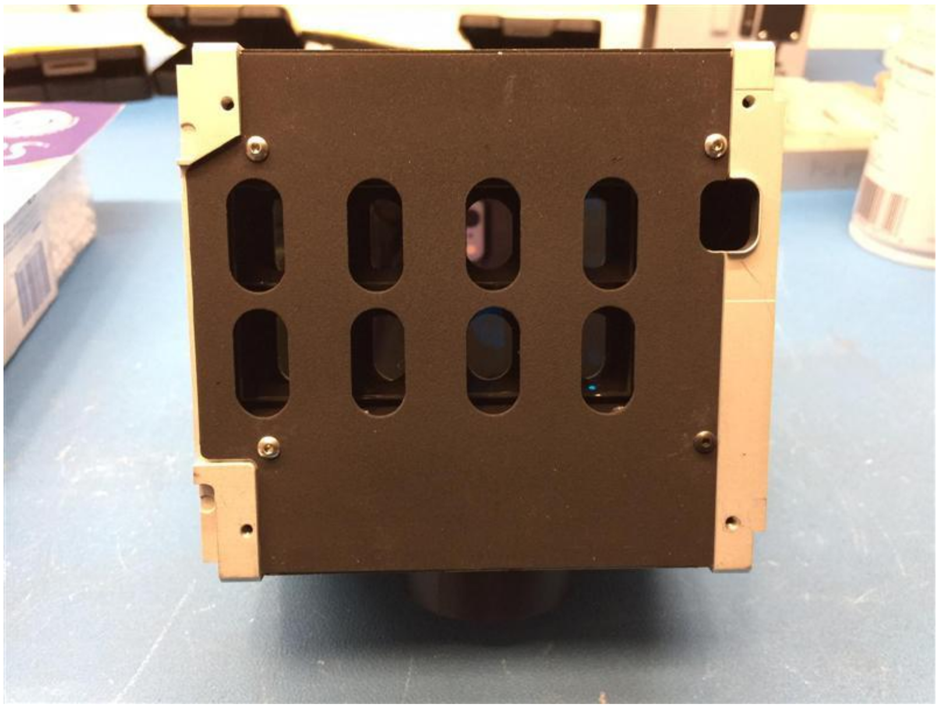
Overview: Hawkeye has been designed to minimize polarization sensitivity, specifically by using a single wedge polarization scrambler to cause the polarization to vary across the aperture, and the use of most components at normal incidence. Its polarization was measured by rotating a sheet polarizer, either designed for the visible or near infrared, in front of the aperture while the instrument viewed a 12 inch integrating sphere illuminated by either an LED-based microscope illuminator, or a tungsten-lamp based microscope illuminator. While the sphere, loaned to us by NASA, has built in lamps, there are too bright and too hot for this measurement, which required rotating the polarizer by hand during a scan for expediency. The instrument showed a surprising amount of sensitivity to polarization.

Setup: The instrument was oriented in front of the sphere in the orientation shown in Figure One.

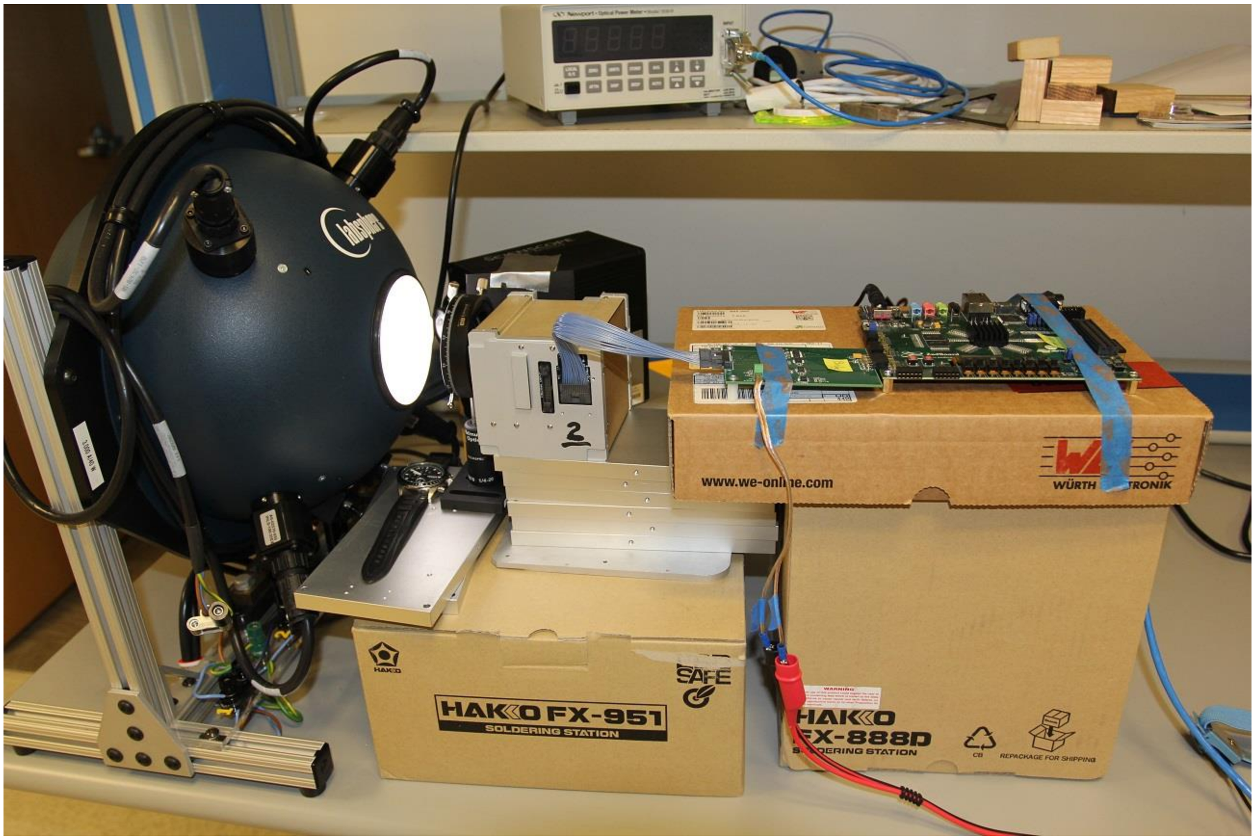
Figure One: Orientation of Instrument During Illumination



The finderscope aperture is at the upper right, and Band 7 is the closest aperture to the finderscope.

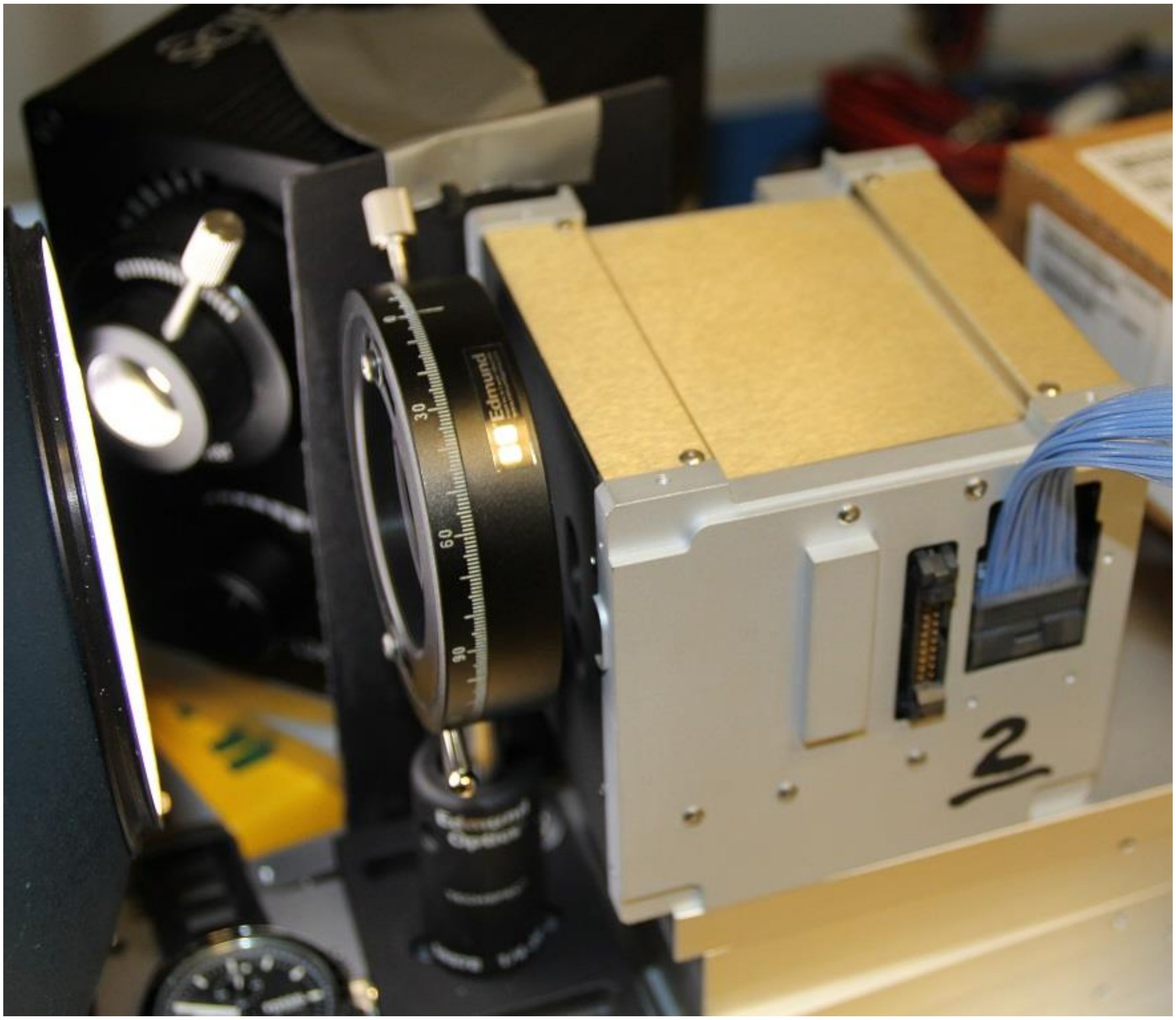
The instrument was mounted in front of the sphere as shown in Figure Two.

Figure Two: Instrument Viewing Sphere through Polarizer



The polarizer was mounted in a fixture such that, at the zero degree position, the polarizer extinguished a glint off of a surface like the floor or a desk at an angle 60 degrees off normal. Since the glint off a surface is dominated by light that is polarized perpendicular to the plane of incidence, this means that zero degrees corresponds to preferentially passing vertically polarized light in Figure One; the E-field transmitted is vertical. A positive angle of rotation of the polarizer was in the counter-clockwise direction, as shown in Figure Three.

Figure Three: A Positive Angle was Counter-Clockwise.

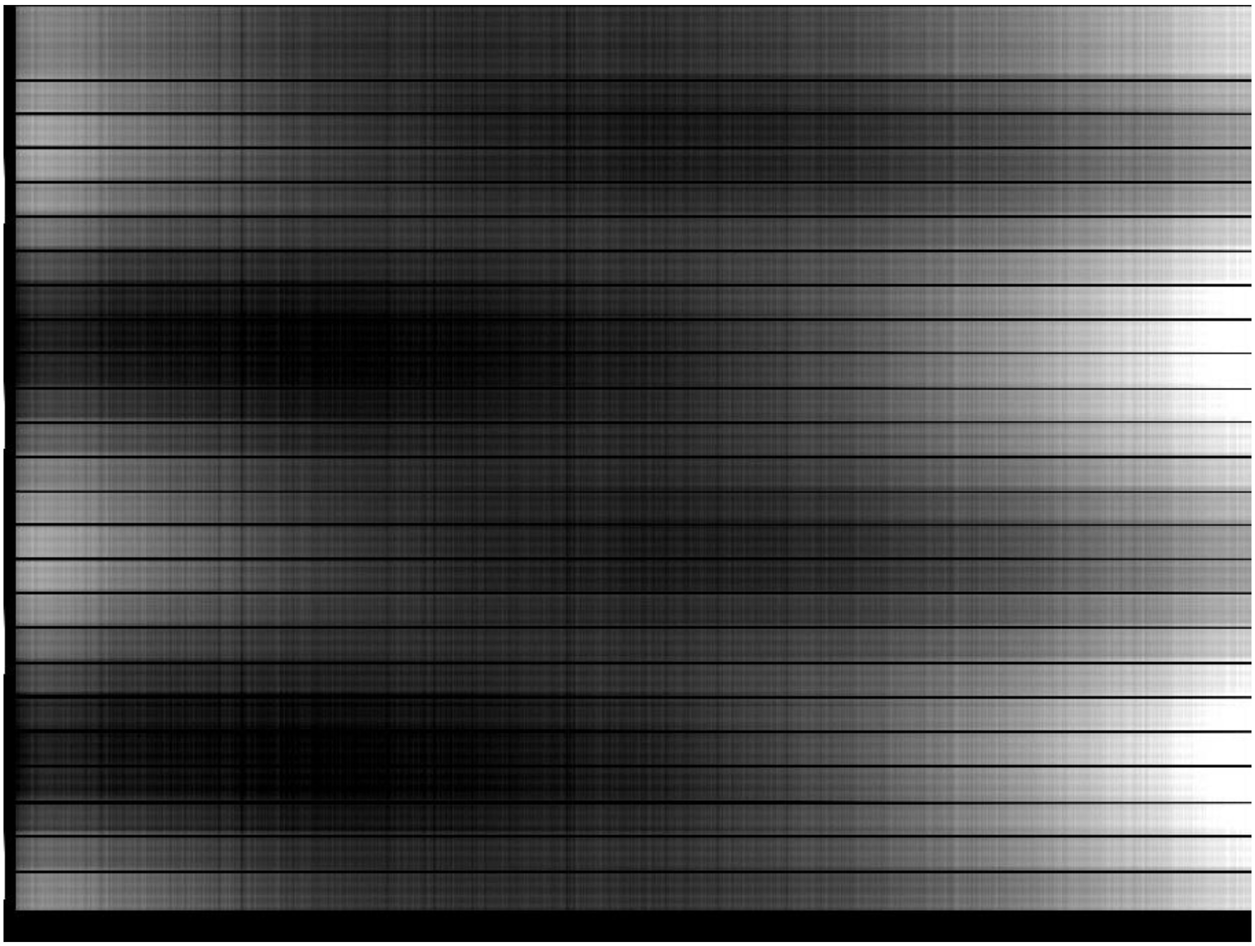


With respect to the instrument coordinate system, a zero degree polarizer orientation means light polarized in the +/-Y direction is preferentially passed, and a positive angle in my measurement is from the –Y face of the instrument toward the +Z face. As will be seen in the data presented later, most bands showed an enhancement in response at low pixel numbers at a 45 degree positive rotation. Low pixel numbers correspond to light arriving from the +Y direction relative to nadir, which is coming up from below in Figure One.

An LED based microscope illuminator was used for all bands except for bands 7 and 8, where a tungsten based illuminator was used. For Bands 7 and 8 we used a near infrared polarizer from Edmund Scientific. For Bands 1 through 6 we used a visible spectrum polarizer.

Our test sequence is that we would take a single long exposure for each band, capturing data at 5 lines a second. Each test would begin with a 20 second segment at zero degrees polarization, followed by incrementing the polarizer by either 30 degrees (Unit 1), or 15 degrees (Unit 2). After incrementing the polarizer the operator would momentarily block the light with his fingertips. We used 4:1 oversampling and no aggregation during data collection for both units, using only the green Chroma channel for each band, so only one stripe results from the momentary blocking. 64 lines of dark data concluded each data set. A sample data set for Unit 2 Band 7 is shown in Figure Four.

Figure Four: Sample data set: Unit 2 Band 7



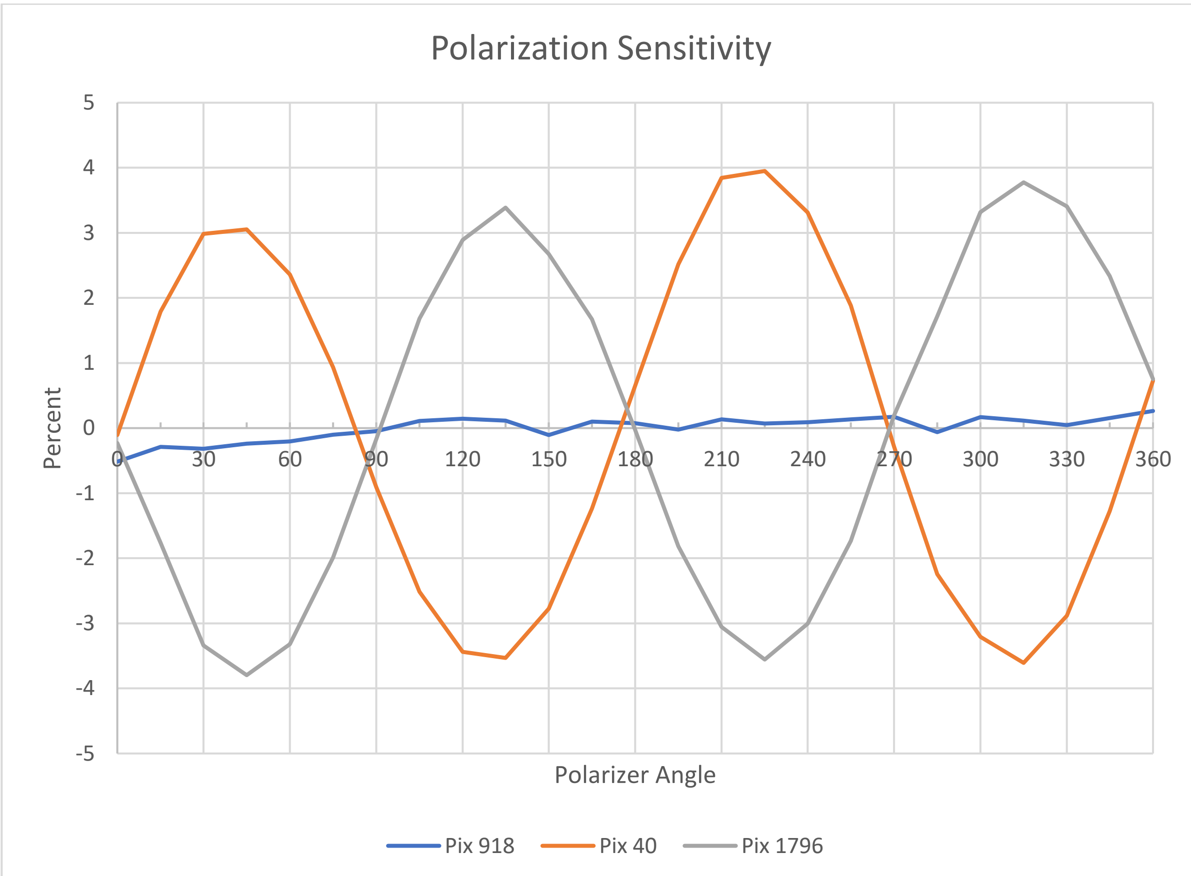
This data set has samples every 15 degrees. It is apparent there is a brightening on the left side (low pixel number) at about 45 degrees polarizer rotation, followed by a minimum at 135 degrees. High pixel numbers show an inverse effect.

Most radiometric instruments, such as MODIS, would take a separate file for each polarization angle. We did not do this because of greater demands on sphere stability, and the much greater workload.

Results: we were not expecting much polarization sensitivity since we use an array detector at near normal incidence, and even included a single wedge polarization scrambler from Karl

Lambrecht. Indeed, we found very little polarization sensitivity on-axis. However, off-axis sensitivity was significant. Figure Five shows a typical variation of response, with angle, as a function of pixel number. Every single band had the same pattern. The only parameter that varied was the magnitude.

Figure Five: DOP for Band 6 Unit 2



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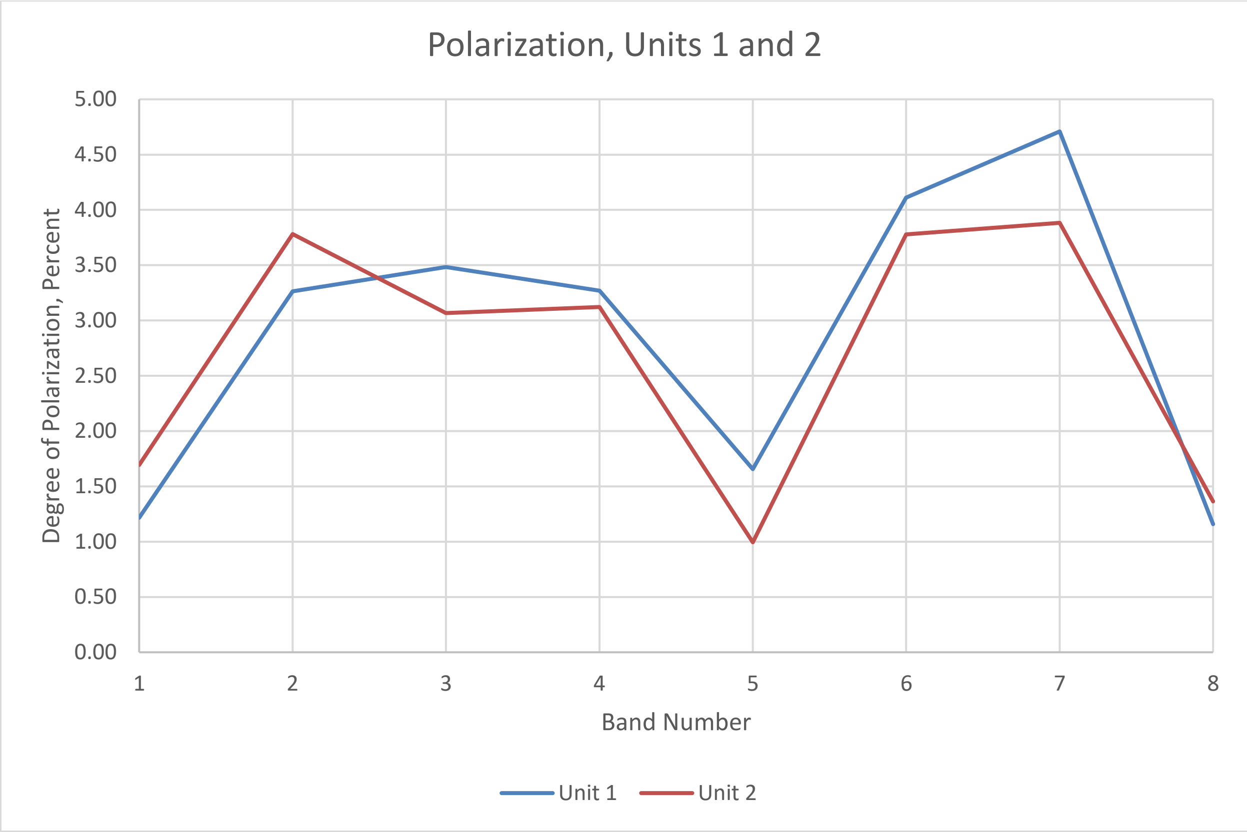
Some bands showed a slight amount of slope in the data as the CCD warmed up during the exposure. When the signal was quite low, for certain bands, the gradient was corrected, but with little effect on the result.

Figure Six illustrates the degree of polarization for all bands, both units. The degree of polarization in percent is defined as:

$$DOP = 100*(Max-Min)/(Max+Min),$$

where the maximum or minimum is over the 360 degree range of polarizer angle.

Figure Six DOP Summary, both Units



The DOP of polarization varies linearly across the length of the CCD. We did quite a bit of experimentation to try and determine why it was so large. We found the passband filters had a much larger polarization sensitivity with angle than we expected, in one case a 14% variation in transmission with polarization at an off-axis angle of around 10 degrees. Our measurement of the filter effect was not very accurate due to limitations on making a measurement with a tilted filter, but it was clearly significant. All filters were mounted with a 2 degrees off-axis offset relative to the detector centerline to eliminate retro-reflection of stray light from the detector surface back to the detector, as were the scramblers, and this asymmetry leads to the left-right effect. I have attached an Appendix to this report illustrating my thinking.

The polarization for each band is listed in Table One.

Table One: Instrument Degree of Polarization

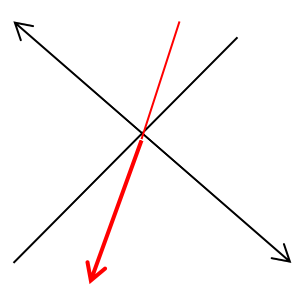
Band	Average Unit 1	Average Unit 2
1	1.22	1.69
2	3.26	3.78
3	3.48	3.07
4	3.27	3.12
5	1.66	0.99
6	4.11	3.78
7	4.71	3.88
8	1.16	1.36

(Note: when applying these numbers to the data be sure to take into account the sign, as can be gleaned from Figure Six and the discussion of polarizer orientation during measurement)

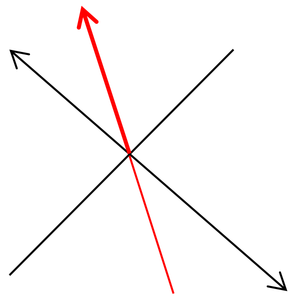
In a future instrument a double wedged polarization scrambler could be used, which would reduce this sensitivity considerably. It would be 4 mm thicker, but would probably fit. Some improvement may be possible by reducing off-axis filter sensitivity.

Appendix A: Why does this Effect Occur?

Here is my reasoning regarding the polarization at 45 degrees. It is predicated on the filter introducing considerable polarization due to its bandpass changing when tilted, at different polarizations. I don't know why it does that, but that's what I measured. So, for now, assume the 14% drop in throughput at one polarization over the other for an off-axis filter is real. Here is what is caused by the 2 degree tilted filter. Below I show what the 45 degree polarization case looks like projected on the filter from 10 degrees above, with the filter tilted 2 degrees.



The arrows at 45 degrees mark the input polarization and the red arrow marks the plane of incidence on the surface. Here is what the pattern looks like from 10 degrees below:



Try inspecting a tilted box to verify my thinking is right. Based on a lot of trig and coordinate transformations, at which I am very rusty, I calculated the red arrow to be 12 degrees off the vertical. Note that the projection on the polarization axes reverses, which causes the sign change left-right. In the top figure the plane of incidence is 45+12, or 57 degrees off the polarization axis. In the bottom figure it is 45-12, or 33 degrees off the polarization axis. This means the effect of the polarization on the filter will be about 15% of worst case or, for my 14 percent input polarization, about 2.1%. That is in the right order of magnitude for what I see. So, this is my theory as to where the left-right variation comes from.