VCST Internal Memo

Title: Assessment of FP-11 Polarization Sensitivity for the VIIRS F2 VisNIR Bands
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References

[1] TP1544640-2222 Rev A, 'Polarization Sensitivity FP-11 Test Procedure,' Raytheon.
[2] VCST_TECH_REPORT_13_048, 'Preliminary Analysis of FP-11 Polarization Sensitivity Data,' Jeff McIntire, December 31, 2013.
[3] VCST_TECH_REPORT_14_002, 'Preliminary Analysis of FP-11 Polarization Sensitivity Special Test Data,' Jeff McIntire, January 2, 2014.
[4] VCST_TECH_REPORT_14_012, 'Summary of Preliminary Analysis of FP-11 Polarization Sensitivity Data,' Jeff McIntire, January 28, 2014.
[5] 'VIIRS J1 FP-11 Polarization Quicklook,' Dave Moyer, December 29, 2013.
[6] 'JPSS J1: Results from FP-11 Polarization Ambient,' Raytheon, January 9, 2014.
[7] VIIRS PRD Rev C, 'Joint Polar-orbiting Satellite System (JPSS) Visible Infrared Imaging Radiometer Suite (VIIRS) Performance Requirements Document (PRD).'
[8] VIIRS.10.15.036, 'Polarization Test Source Assembly (PTSA) Calibration and Performance Verification,' Josh Cohen, Dan Tiffany, Eslim Monroy, and Tung Wang, November 13, 2013.
[9] Mathematical Methods in the Physical Sciences, Mary L. Boas, John Wiley & Sons, 1985.
[10] NICST_MEMO_10_022, 'Polarization Sensitivity Analysis of VIIRS F1 VisNIR bands,' Junqiang Sun, August 16, 2010.

1. Introduction

VIIRS F2 sensor polarization sensitivity was measured for the VisNIR bands during FP-11 in ambient phase II testing [1]. Preliminary Analysis was reported in [2-6]. This work will provide an overview of the test setup and objectives, analysis methodology, and results (both baseline testing and additional special testing performed after the nominal FP-11 was completed).

2. Objective

The objective of the FP-11 test was to determine the sensitivity of the VIIRS instrument to input linearly polarized light. There are two specifications which relate to the polarization sensitivity of VIIRS [7]:

> **V_PRD-12624** – The VIIRS Sensor linear polarization sensitivity of the VIS and NIR bands shall be less than or equal to the values indicated in Table 1 for scan angles less than 45 degrees off Nadir.
>
> **V_PRD-12667** – The VIIRS Sensor linear polarization sensitivity shall be measured within a characterization uncertainty of 0.5% (one sigma) for scan angles less than 55.84 degrees off Nadir.

Only the first specification will be addressed in this memo; the second will be addressed in a subsequent memo.

2. Test Equipment

The Polarization Test Source Assembly (PTSA) was used to measure the polarization sensitivity of the VIIRS F2 sensor [1]. This setup consisted of an integrating sphere, polarizer sheets, shaping filters, and various baffling [8]. VIIRS was placed on a rotating mount such that the angle at which VIIRS viewed the PTSA could be varied. The PTSA was viewed at the following VIIRS scan angles: -55, -45, -20, -8, 22, 45, and 55 degrees. A general schematic of the test setup is shown in Figure 1 indicating the placement of the filters and polarizers relative to the path.

An integrating sphere (SIS-100-2) was used as a source for FP-11 testing. The SIS-100-2 is a 100 cm integrating sphere with a 12 inch circular aperture. The spectral output of the SIS-100-2 is shown in Figure 2 for three different lamp levels: ABCDEFG was used with the Sonoma filter, BDF was used without any shaping filter, and ABCDEFGHJK was used with the Hoya filter (see below for filter descriptions).

Two different polarization sheets were used during testing: BVONIR and BVO777. These polarizers were mounted on a rotary stage which could be cycled between 0 and 360 degrees. A second fixed polarizer of each type was used in conjunction with the first to measure the polarizer efficiency. The maximum and minimum transmittance for both polarizers is shown in Figure 3 and their respective degrees of linear polarization are plotted in Figure 4.

The two shaping filters used during testing were the Sonoma and Hoya filters. The Sonoma filter is a long wave blocking filter with very low transmittance above about 650 nm. The Hoya filter was used during special testing after the end of the nominal FP-11 testing, and simulates the TOA spectra. The transmittance of the two shaping filters is plotted in Figure 5. Figure 6 shows the source spectra for all the test configurations measured in FP-11 with the BVONIR polarizer in comparison to the TOA spectra.

In addition, a lollipop obscuration was inserted into the optical path to investigate possible stray light contamination.

3. Test Configuration

Four test configurations were used during nominal FP-11 testing: BVONIR with the Sonoma filter, BVO777 with the Sonoma filter, BVO777 without the Sonoma filter, and BVONIR without the Sonoma filter. Stray light, efficiency, and polarization sensitivity tests were performed for each configuration.

First, a stray light investigation was performed for each configuration by performing two tests: one with the source off and the room dark, and the other with the source on and a lollipop obscuration inserted into the path. The rotating polarizer was then cycled through 25 different angles from 0 to 360 degrees in 15 degree increments for both tests.

Next, a second fixed polarizer was inserted into the path between the rotating polarizer and VIIRS for all four configurations. The rotating polarizer was then cycled through 25 different angles from 0 to 360 degrees in 15 degree increments.

Lastly, the polarization sensitivity of VIIRS instrument was measured for all four configurations. The BVO777 configurations were only measured once at a scan angle of -8 degrees; the BVONIR configurations were measured at all 7 scan angles including three repeated measurements at -8 degrees. The configurations with the Sonoma filter were used to measure the sensitivity of bands M1 – M3, while the sensitivity for bands I1 – I2 and M4 – M7 was measured without the Sonoma filter. However, useful data was collected for some bands in both configurations (with and without the Sonoma filter).

Additional testing was performed after the completion of nominal FP-11 testing as described above. For this testing, only the BVONIR polarizer was used and all data was collected at -8 degrees scan angle. First, cross hairs at the aperture stop were removed. Next, the upper half of the VIIRS telescope aperture was blocked, followed by the blocking of only lower half. This provided some additional information for the Raytheon polarized transmittance model by measuring the polarization sensitivity to different portions of the mirrors inside VIIRS and different incident angles on the filters. These three tests were performed with and without the Sonoma filter. Then, a test was performed using the Hoya filter instead of the Sonoma filter. Lastly, three tests were performed with the Sonoma filter during which the stray light baffling was removed.

4. Methodology

A standard Fourier analysis was used to determine the polarization sensitivity of the VIIRS instrument [9]. The Fourier expansion is written as

$$dn = \frac{1}{2}c_0 + \sum_n c_n \cos(n\alpha) + \sum_n d_n \sin(n\alpha), \qquad (1)$$

where the Fourier coefficients are defined by the following:

$$c_n = \frac{1}{\pi}\int_{-\pi}^{\pi} \cos(n\theta)\, dn(\theta)\,\partial\theta, \qquad (2)$$

and

$$d_n = \frac{1}{\pi}\int_{-\pi}^{\pi} \sin(n\theta)\, dn(\theta)\,\partial\theta. \qquad (3)$$

In this work, only the zeroth through fourth order Fourier coefficients were calculated (for the polarizer efficiency tests, only the zeroth and second order terms were calculated). Eq. (1) can be rewritten as

$$dn = \frac{1}{2}c_0\left[1 + \sum_{n=1}^{4} a_n \cos(n\alpha - \delta_n)\right], \qquad (4)$$

where the linear polarization sensitivity of the instrument (referred to below as the polarization factor) is defined as

$$a_n = \frac{\sqrt{c_n^2 + d_n^2}}{\frac{1}{2}c_0\sqrt{DoLP}} \qquad (5)$$

and the phase angle is defined as

$$\delta_n = \tan^{-1}\left(\frac{d_n}{c_n}\right). \qquad (6)$$

The degree of linear polarization (DoLP) of the input light is defined as

$$DoLP = \frac{\sqrt{c_2^2 + d_2^2}}{\frac{1}{2}c_0}, \qquad (7)$$

determined from the cross polarizer efficiency testing.

5. Analysis

The data analyzed during the nominal FP-11 testing is listed in Tables 2 – 5 (including the type of test, number of collects, scan angle, and samples used). In this work, 30 EV samples were used in the processing. The sample window was chosen to minimize the stray light observed in the lollipop obscuration test. The OBC BB view data was used as a dark reference, averaged per scan, and subtracted from each EV pixel of the corresponding scan. Then all EV pixels were first averaged over a particular scan and then all scans were averaged in each collect (a 3-sigma outlier rejection was used in each average). Note that the BB data was first truncated from 14 to 12 bits in order to remove any bias between the EV and BB data.

Each collect corresponded to a measurement at a discrete polarizer sheet angle. The angle was cycled from 0 to 360 degrees in 15 degree increments. This set of 25 measurements was then used to determine the Fourier coefficients in Eqs. (2) and (3), and finally the linear polarization sensitivity and phase from Eqs. (5) and (6). First the cross polarizer efficiency test was analyzed; then the efficiency correction defined by Eq. (7) was used in the final polarization sensitivity calculation.

A series of special tests were run after the conclusion of the nominal testing, the data collected from which is listed in Table 6. The tests were conducted to provide additional information regarding the baseline testing and improve the Raytheon modeling of the polarized transmittance

6. Results

Data from the stray light tests was analyzed for all configurations for both the dark and lollipop tests. The stray light observed for all detectors in band M7 is shown in Figures 7 (dark) and 8 (lollipop) using the BVONIR polarizer without the Sonoma filter. The stray light observed in the dark configuration is consistent with zero. Some small positive signal was recorded using the lollipop configuration (less than 0.2 dn for all detectors except detector 16, for which the signal was 0.2 – 0.3 dn). All other bands showed similar results (all detectors less than 0.2 dn); the only other exceptions were M6 detector 16 and I2 detector 32 (both less than 0.6 dn). Ideally, any stray light would constitute a pedestal that would need to be subtracted from the polarization sensitivity measurements; however, given the low levels of stray light observed, not additional processing was conducted.

Cross polarizer test data was analyzed for all configurations and the DoLP of the polarizers in each configuration was determined. The efficiency was calculated for each band, detector, and HAM side; the results for the BVONIR with (black) and without (red) the Sonoma filter are shown in Figure 9 (HAM side A is shown here, but HAM side B results are consistent). For each band, the detectors are plotted on the horizontal axis. Note that there is good agreement between the measurements for most detectors in M1 – M3; the signal is much lower for these bands without the Sonoma filter, and so the efficiency is less well determined. Also, the Sonoma filter blocks only part of the in-band I1 radiance; as a result, the efficiencies for the different configurations are not consistent. For the remaining bands, the signal with the Sonoma filter was too low to reliably determine the DoLP. Figure 10 shows the calculated BVO777 polarizer efficiencies with (black) and without (red) the Sonoma filter for HAM side A. The efficiencies agree less well between the two configurations, and in some cases efficiencies of greater than 100 % were observed (which is unphysical). This must be regarded as uncertainty in the measurement.

The polarization sensitivity was derived for all VisNIR bands, detectors, HAM sides, and seven scan angles. Figure 11 plots the measured dn for band M7, HAM side A using the BVONIR polarizer without the Sonoma filter at a scan angle of -8 degrees (UAID 4301893). The lines indicate the calculated Fourier series using the zeroth through fourth order terms; the Fourier series reproduces the observed behavior very well. Note that the amplitude and phase of the Fourier series varies with detector. Figure 12 shows the zeroth through fourth order Fourier coefficients for M7, HAM side A versus scan angle for all detectors. Only the zeroth and second order terms show non-negligible results. The results shown in Figures 11 and 12 are indicative of all VisNIR bands. Figure 13 compares the second order term a_2 across test configurations and repeated measurements at a scan angle of -8 degrees (band M1, HAM side A). The repeated measurements at -8 degrees generally agree well for each BVONIR configuration; between the two BVONIR configurations, the agreement is also good (here the factors derived from data without the Sonoma filter were less well determined due to low signal). The two BVO777 configurations also show good agreement, with the same limitations as seen using the BVONIR polarizer. There is some difference between the BVONIR and BVO777 polarizer data (about a constant 0.5 % across detectors). Offline analysis indicates that the DoLP for the BVO777 changes significantly across the M1 bandpass, whereas the BVONIR DoLP is more constant (see Figure 4). The results shown in Figure 13 are representative of all VisNIR bands, with a couple caveats. First, the difference between BVONIR and BVO777 is smaller for all other bands, except where BVO777 efficiency is low (in the I2 and M7 bandpass). Second, where the Sonoma filter excludes part of the bandpass (I1 and M5), the polarization sensitivity does not agree well between configurations. This indicates that the spectral dependence of the polarization sensitivity changes over the bandpass.

The final polarization factors (a_2) are shown for all bands, detectors, and scan angles in Figure 14 (15) for HAM side A (B). The maximum values per band and scan angle are shown in Table 7 (8) for HAM side A (B). The final polarization results were derived using the BVONIR with the Sonoma filter for M1 – M3 and without the Sonoma filter for I1 – I2 and M4 – M7. The first specification in Section 2 applies directly to a_2 for scan angles less than 45 degrees. For some scan angle – detector combinations, bands M1 – M4 are non-compliant with the specification (up to ~ 6.4 % for M1, ~4.3 % for M2, ~2.9 % for M3, and ~4.2 % for M4). There is also noticeable HAM side dependence with up to about 1.0 % difference, where the HAM side B results are generally larger. Also, note that there is considerable variation both with detector and with scan angle (greater than 4 % for M1 at -55 degrees scan angle). The VIIRS F1 a_2 are also listed in Tables 7 and 8 for comparison [10]; note that for almost all cases, F2 has larger polarization sensitivity than F1. The corresponding final polarization phases (δ_2) are shown for all bands, detectors, and scan angles in Figure 16 (17) for HAM side A (B). The phase determination becomes difficult when a_2 is small, as a small change in the c_2 or d_2 causes a large change in δ_2 when c_2/d_2 approaches 0 or 1.

The resulting a_2 derived from special testing are shown in Figure 18 in comparison to the nominal testing results measured at -8 degrees scan angle. Note that differences between the nominal results and testing in which the cross hairs and baffling were removed are very small. As expected, blocking the upper or lower half of the telescope aperture showed some differences; this results from different portions of the mirrors being illuminated and different angles of incidence on the dichroic and the filter assembly. The differences between the nominal testing and the special testing with the Hoya shaping filter are shown in Figure 19. All bands showed less than 0.2 % difference from the two different spectra (see Figure 6). The special testing, combined with the multiple test configurations in nominal testing, indicated that the large polarization sensitivity observed in nominal testing was likely not the result of the test setup, and reflected the true performance of the sensor.

7. Summary

FP-11 polarization sensitivity testing was performed under ambient conditions for VIIRS F2 sensor. Analysis showed then following:

- Linear polarization sensitivity for bands M1 – M4 was observed to be higher than the specified limit (as high as ~6.4 % for M1, ~4.3 % for M2, ~2.9 % for M3, and ~4.2 % for M4).
- Differences in linear polarization sensitivity with HAM side are as high as ~1 %, where HAM side B is generally larger.
- Large detector to detector and scan angle differences were observed with bands (up to ~4 % in M1). This is likely the result of angle of incidence changes on the filter assembly.
- Comparisons between test configurations in general agreed (using the BVONIR polarizer sheet with and without the Sonoma shaping filter).
- Special testing conducted after nominal testing and the multiple test configurations in nominal testing indicated that the large polarization sensitivities observed likely reflected the true performance of the sensor, and not the test configuration.

Table 1: Specified maximum polarization sensitivity [7]

Band	Sensitivity [%]
I2, M1, M7	3
I1, M2, M3, M4, M5, M6	2.5

Table 2: Data used in the nominal FP-11 test analysis using the BVONIR polarizer without the Sonoma filter

Test type	UAID	Collects	Scan angle	Samples
Stray light – dark	4301878	1 – 25	-8	1625 – 1654
Stray light – lollipop	4301884	1 – 25	-8	1625 – 1654
Efficiency	4301889	1 – 25	-8	1625 – 1654
Polarization Sensitivity	4301893	1 – 25	-8	1625 – 1654
	4301896	1 – 25	55	1975 – 2004
	4301900	1 – 25	-55	55 – 84
	4301904	1 – 25	-45	610 – 639
	4301906	1 – 25	-20	955 – 984
	4301908	1 – 25	-8	1625 – 1654
	4301910	1 – 25	22	1185 – 1209
	4301914	1 – 25	45	1420 – 1449
	4301917	1 – 25	-8	1625 – 1654

Table 3: Data used in the nominal FP-11 test analysis using the BVONIR polarizer with the Sonoma filter

Test type	UAID	Collects	Scan angle	Samples
Stray light – dark	4301875	1 – 25	-8	1625 – 1654
Stray light – lollipop	4301880	1 – 25	-8	1625 – 1654
Efficiency	4301885	1 – 25	-8	1625 – 1654
Polarization Sensitivity	4301894	1 – 25	-8	1625 – 1654
	4301895	1 – 25	55	1975 – 2004
	4301899	1 – 25	-55	55 – 84
	4301901	1 – 25	-45	610 – 639
	4301905	1 – 25	-20	955 – 984
	4301907	1 – 25	-8	1625 – 1654
	4301909	1 – 25	22	1185 – 1209
	4301911	1 – 25	45	1420 – 1449
	4301916	1 – 25	-8	1625 – 1654

Table 4: Data used in the nominal FP-11 test analysis using the BVO777 polarizer without the Sonoma filter

Test type	UAID	Collects	Scan angle	Samples
Stray light – dark	4301877	1 – 25	-8	1625 – 1654
Stray light – lollipop	4301883	1 – 25	-8	1625 – 1654
Efficiency	4301887	1 – 25	-8	1625 – 1654
Polarization Sensitivity	4301892	1 – 25	-8	1625 – 1654

Table 5: Data used in the nominal FP-11 test analysis using the BVO777 polarizer with the Sonoma filter

Test type	UAID	Collects	Scan angle	Samples
Stray light – dark	4301876	1 – 25	-8	1625 – 1654
Stray light – lollipop	4301881	1 – 25	-8	1625 – 1654
Efficiency	4301886	1 – 25	-8	1625 – 1654
Polarization Sensitivity	4301891	1 – 25	-8	1625 – 1654

Table 6: Data used in the special FP-11 test analysis using the BVONIR polarizer

Test type	UAID	Collects	Scan angle	Samples	Filter	Notes
Polarization Sensitivity	4301918	1 – 25	-8	1625 – 1654	Sonoma	Cross hairs removed
	4301920	1 – 25	-8	1625 – 1654		
	4301921	1 – 25	-8	1625 – 1654	Sonoma	Lower half blocked
	4301922	1 – 25	-8	1625 – 1654		
	4301923	1 – 25	-8	1625 – 1654	Sonoma	Upper half blocked
	4301924	1 – 25	-8	1625 – 1654		
	4301927	1 – 20	-8	1625 – 1654	Hoya	
	4301928	1 – 5	-8	1625 – 1654	Hoya	
	4301929	1 – 25	-8	1625 – 1654	Sonoma	Baffling removed
	4301930	1 – 25	-8	1625 – 1654	Sonoma	
	4301931	1 – 25	-8	1625 – 1654	Sonoma	

Table 7: Maximum polarization factors (a_2) for HAM side A

Band	Sensor	Scan Angle						
		-55	-45	-20	-8	22	45	55
I1	F1	1.50	1.24	0.93	0.85	0.70	0.64	0.62
	F2	0.81	0.74	0.73	0.75	0.82	0.84	0.85
I2	F1	0.27	0.29	0.34	0.37	0.47	0.51	0.51
	F2	0.73	0.62	0.36	0.37	0.50	0.61	0.66
M1	F1	2.99	2.63	1.95	1.79	1.42	1.21	1.40
	F2	5.12	5.26	5.54	5.65	5.65	5.50	5.37
M2	F1	2.11	1.97	1.63	1.53	1.28	1.17	1.29
	F2	3.72	3.79	3.90	3.94	3.89	3.96	4.02
M3	F1	1.20	1.14	0.90	0.82	0.61	0.70	0.80
	F2	2.89	2.85	2.73	2.68	2.62	2.79	2.82
M4	F1	1.05	1.10	1.19	1.16	1.00	0.88	0.84
	F2	3.61	3.90	4.16	4.18	4.04	3.88	3.79
M5	F1	1.19	1.02	0.85	0.84	0.76	0.73	0.69
	F2	1.90	1.86	1.82	1.79	1.81	1.80	1.80
M6	F1	0.99	0.96	0.94	0.94	0.88	0.82	0.76
	F2	1.61	1.32	0.86	0.79	0.73	0.74	0.76
M7	F1	0.17	0.19	0.25	0.28	0.38	0.42	0.41
	F2	0.73	0.62	0.36	0.32	0.44	0.55	0.60

Table 8: Maximum polarization factors (a_2) for HAM side B

Band	Sensor	Scan Angle						
		-55	-45	-20	-8	22	45	55
I1	F1	0.86	0.76	0.62	0.59	0.54	0.58	0.61
	F2	0.85	0.89	0.94	0.94	1.00	1.03	1.03
I2	F1	0.49	0.45	0.47	0.51	0.56	0.56	0.55
	F2	1.19	0.92	0.50	0.48	0.53	0.58	0.61
M1	F1	3.14	2.73	2.01	1.83	1.45	1.23	1.39
	F2	5.57	5.73	6.17	6.34	6.41	6.16	5.95
M2	F1	2.25	2.05	1.65	1.54	1.28	1.17	1.30
	F2	4.08	4.08	4.18	4.23	4.19	4.34	4.45
M3	F1	1.45	1.31	0.96	0.85	0.62	0.71	0.81
	F2	2.92	2.86	2.76	2.75	2.85	3.06	3.09
M4	F1	1.59	1.52	1.37	1.30	1.02	0.86	0.82
	F2	4.03	4.20	4.32	4.30	4.15	3.99	3.90
M5	F1	0.81	0.74	0.70	0.69	0.61	0.59	0.57
	F2	2.10	2.17	2.13	2.07	2.02	1.99	1.97
M6	F1	1.29	1.14	0.96	0.92	0.81	0.75	0.70
	F2	1.03	0.92	0.86	0.91	0.95	0.95	0.94
M7	F1	0.52	0.47	0.43	0.44	0.48	0.47	0.45
	F2	1.18	0.92	0.48	0.43	0.47	0.52	0.56

Figure 1: Schematic of the polarization sensitivity test setup

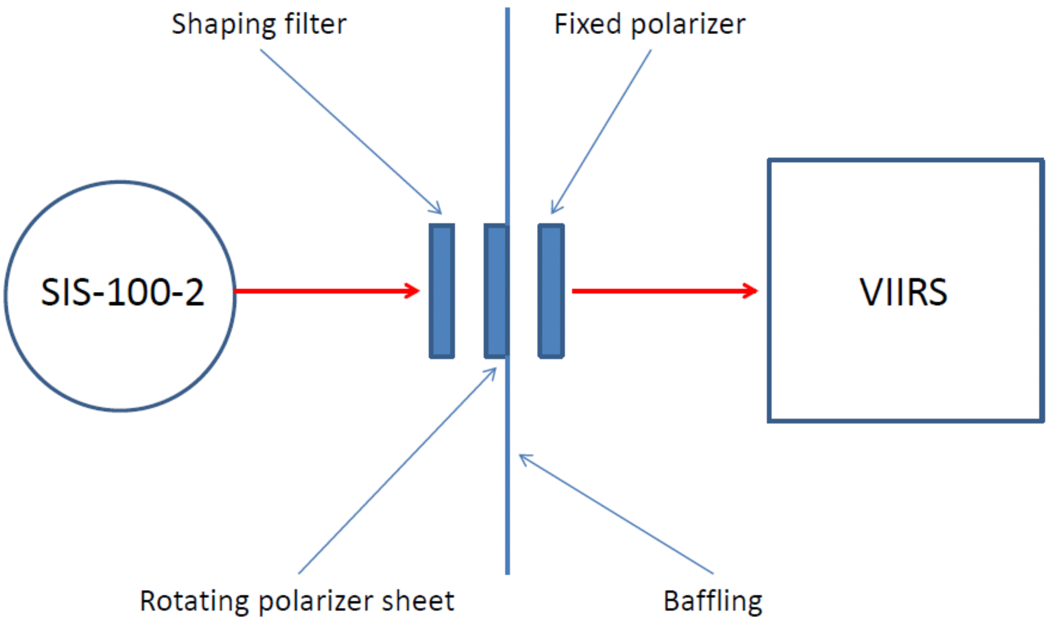

Figure 2: SIS-100-2 spectral profiles for three lamp configurations

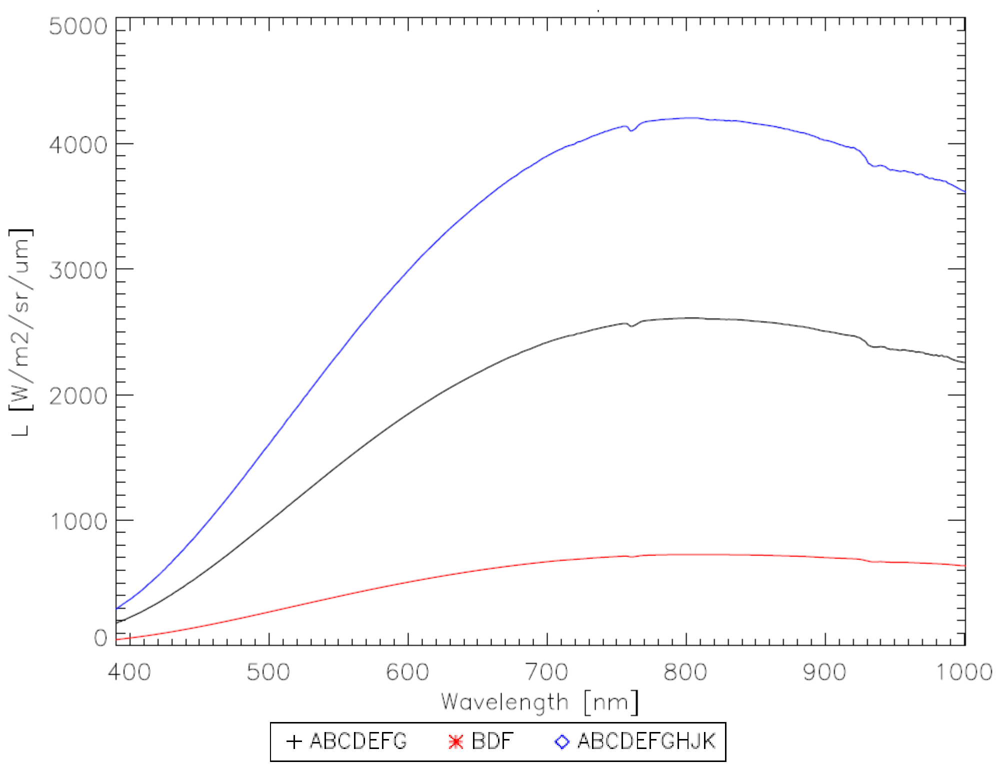

Figure 3: Maximum and minimum transmittance of the BVONIR and BVO777 polarizers

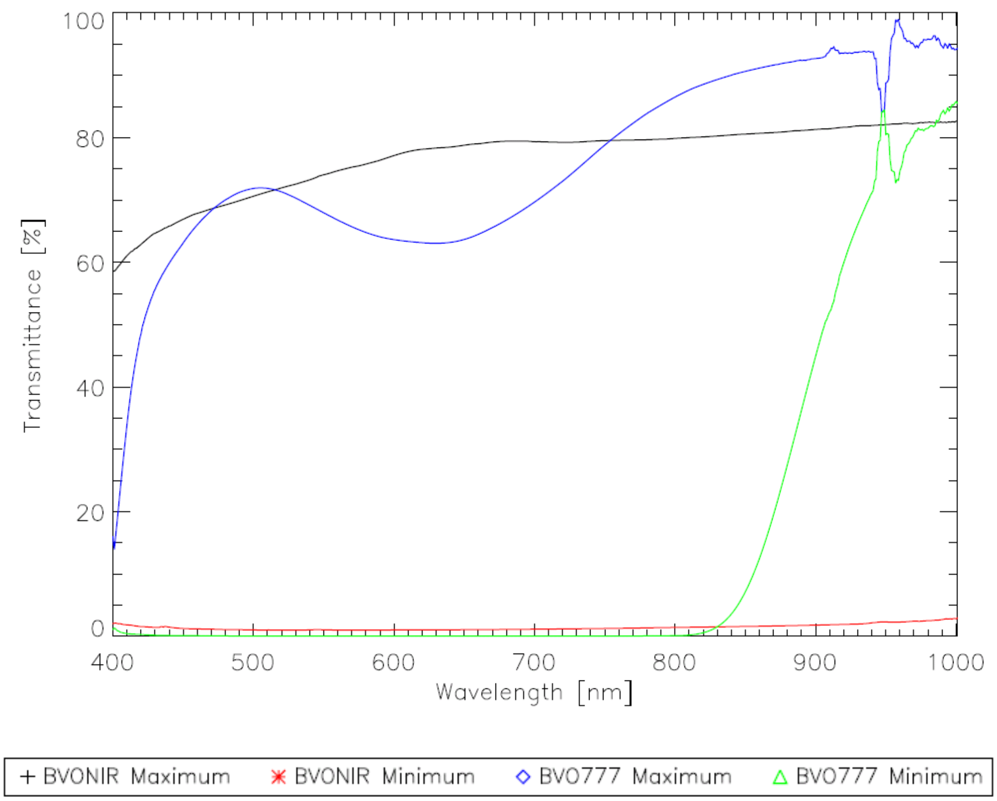

Figure 4: DoLP of the BVONIR and BVO777 polarizers

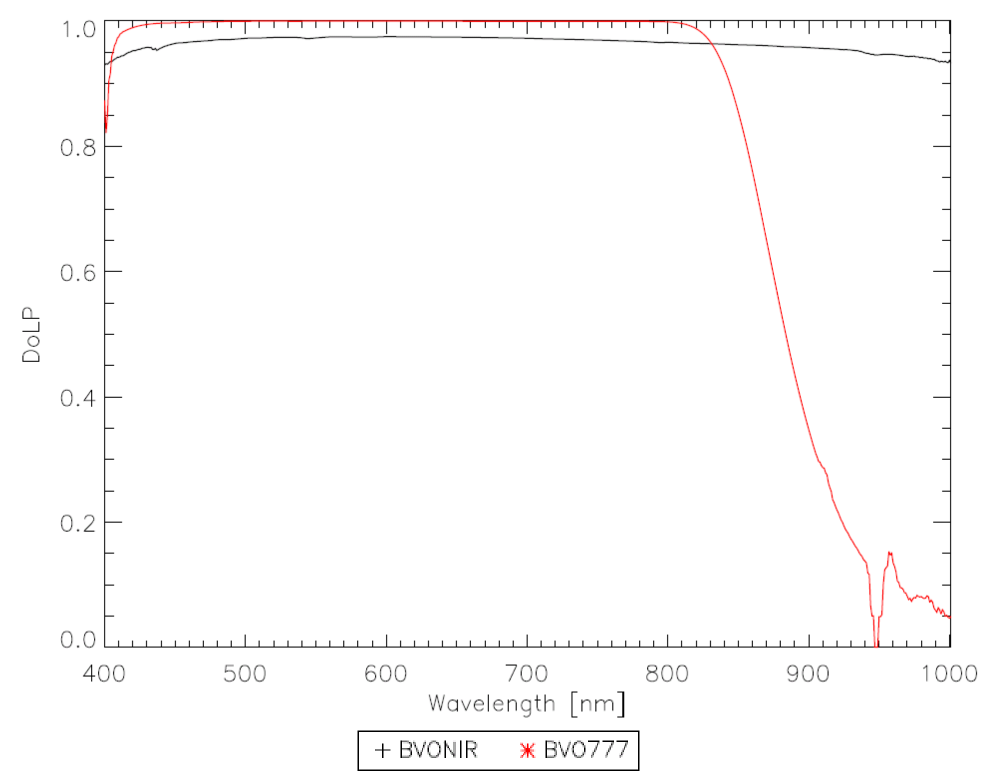

Figure 5: Transmittance of the Sonoma and Hoya filters

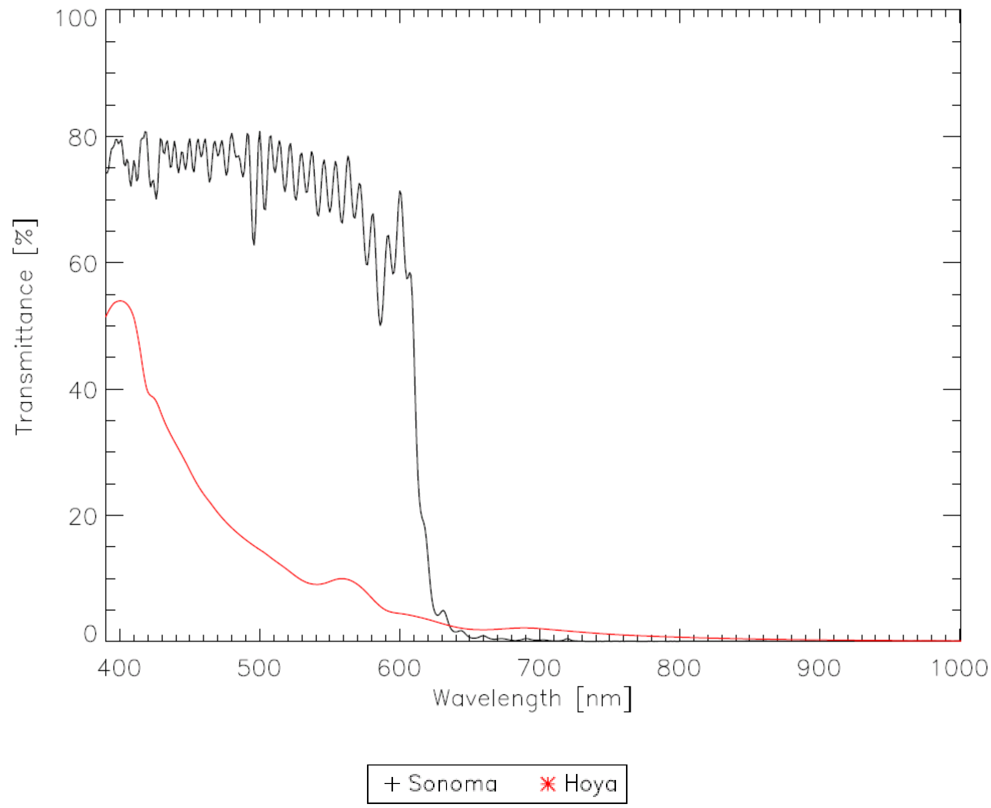

Figure 6: Input spectra for different test configurations

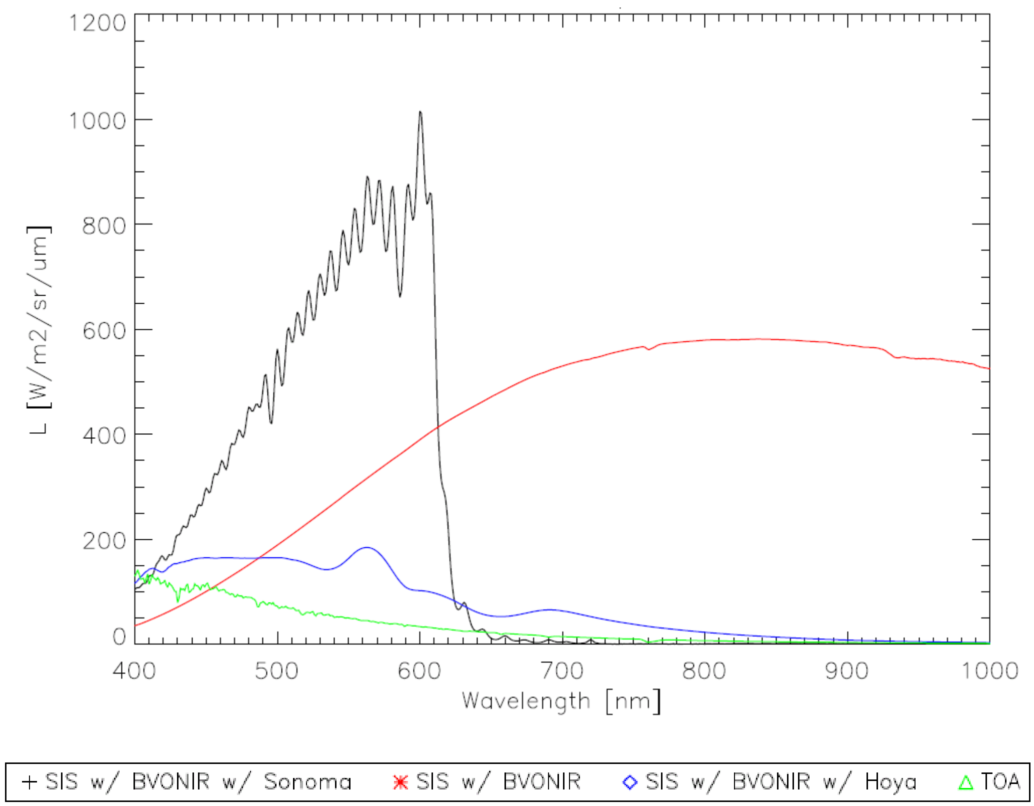

Figure 7: Stray light observed in M7 HAM A using the BVONIR polarizer (no Sonoma filter) with the source dark

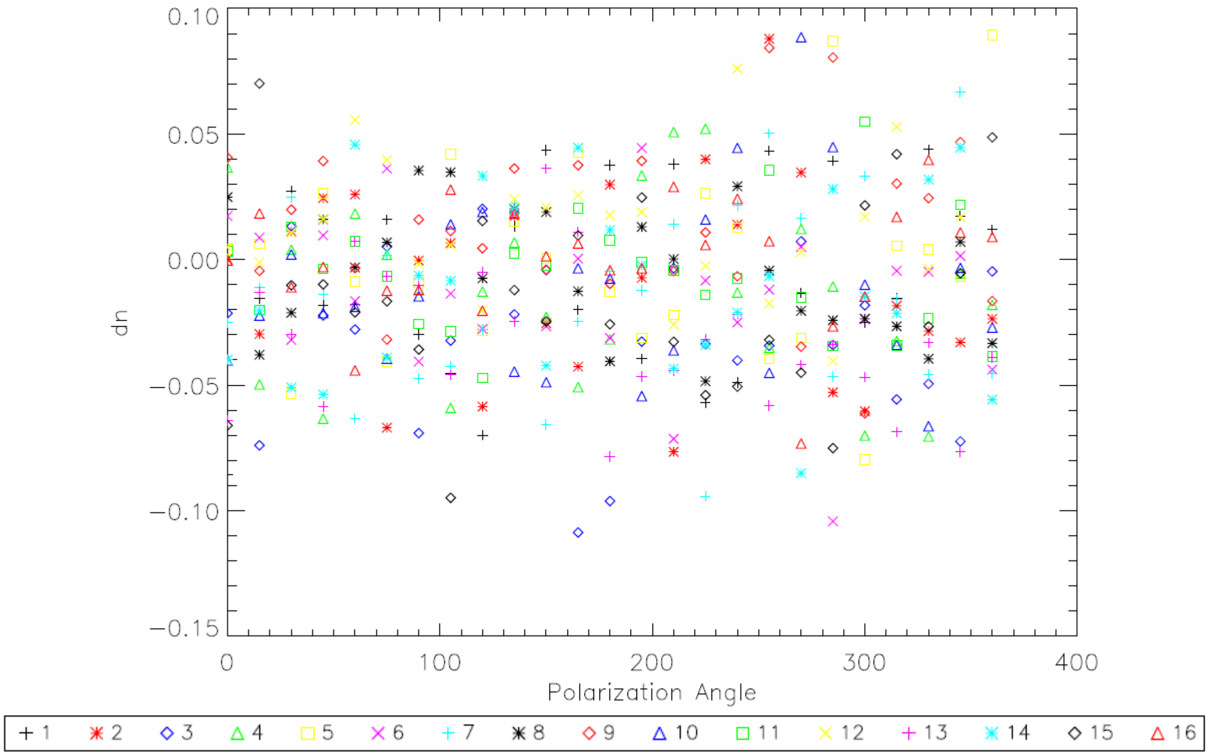

Figure 8: Stray light observed in M7 HAM A using the BVONIR polarizer (no Sonoma filter) with the lollipop obscuration

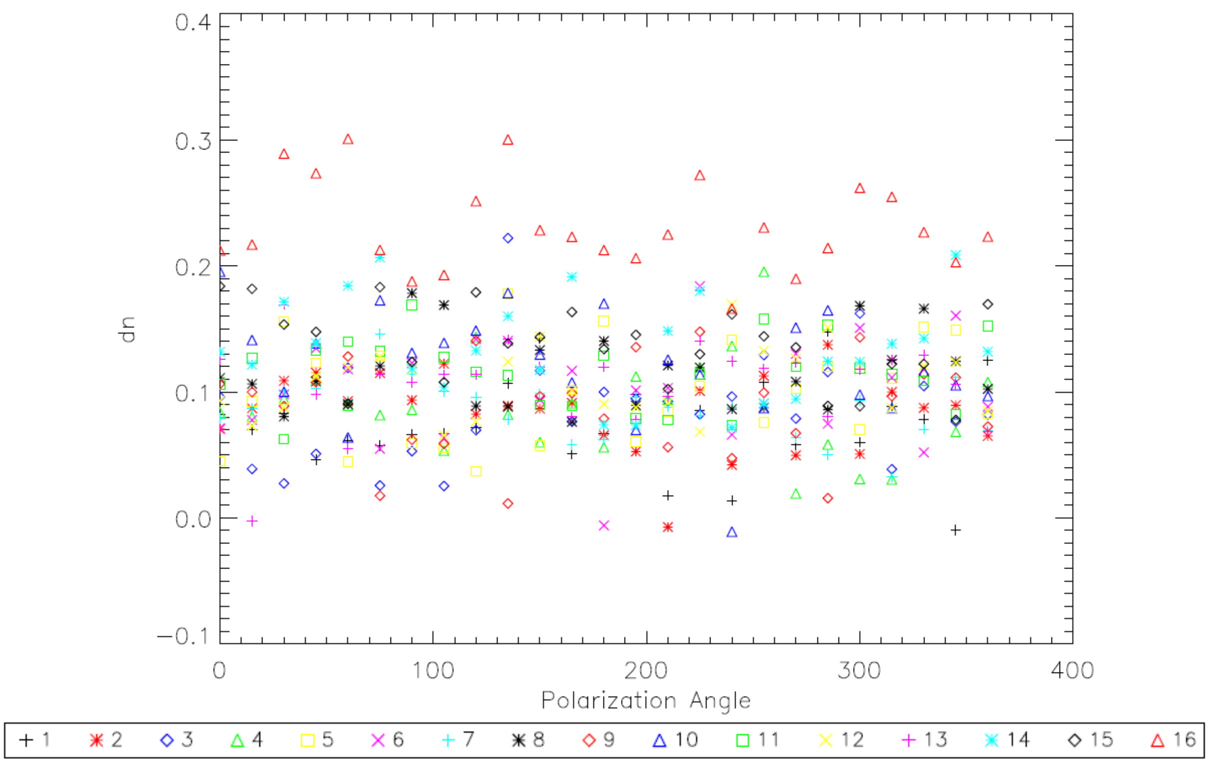

Figure 9: BVONIR polarizer efficiency determined with (black) and without (red) the Sonoma filter

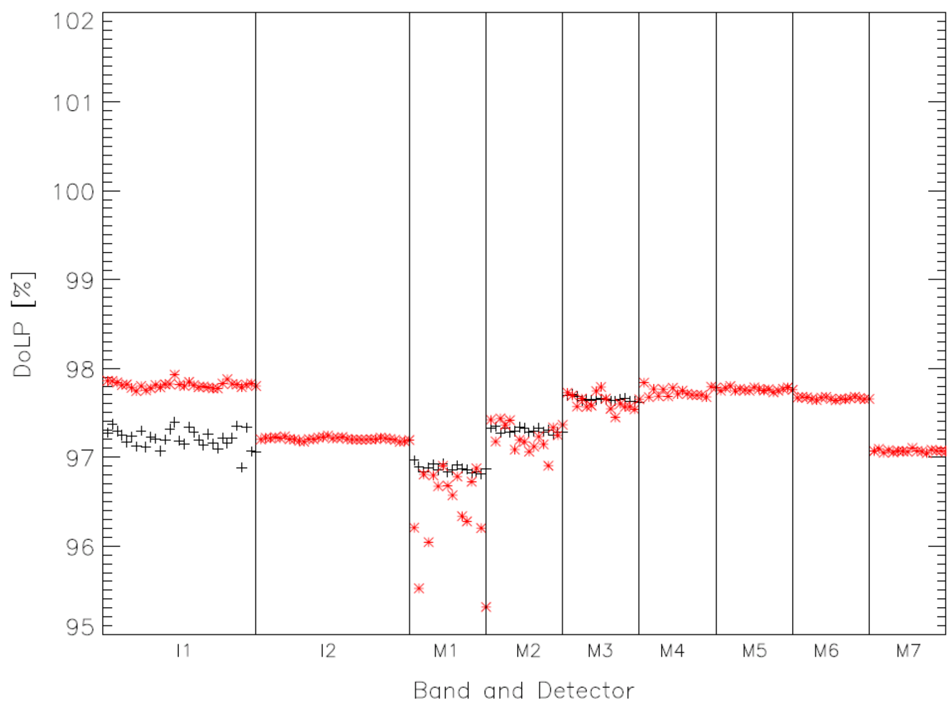

Figure 10: BVO777 polarizer efficiency determined with (black) and without (red) the Sonoma filter

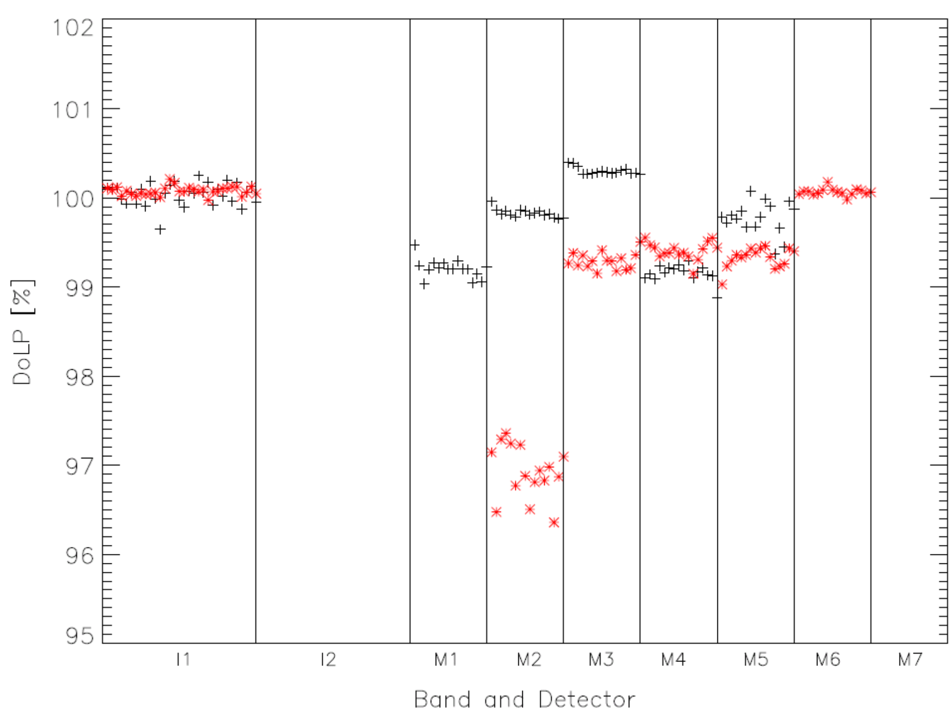

Figure 11: dn as a function of polarizer angle for M7 HAM A using BVONIR without the Sonoma filter

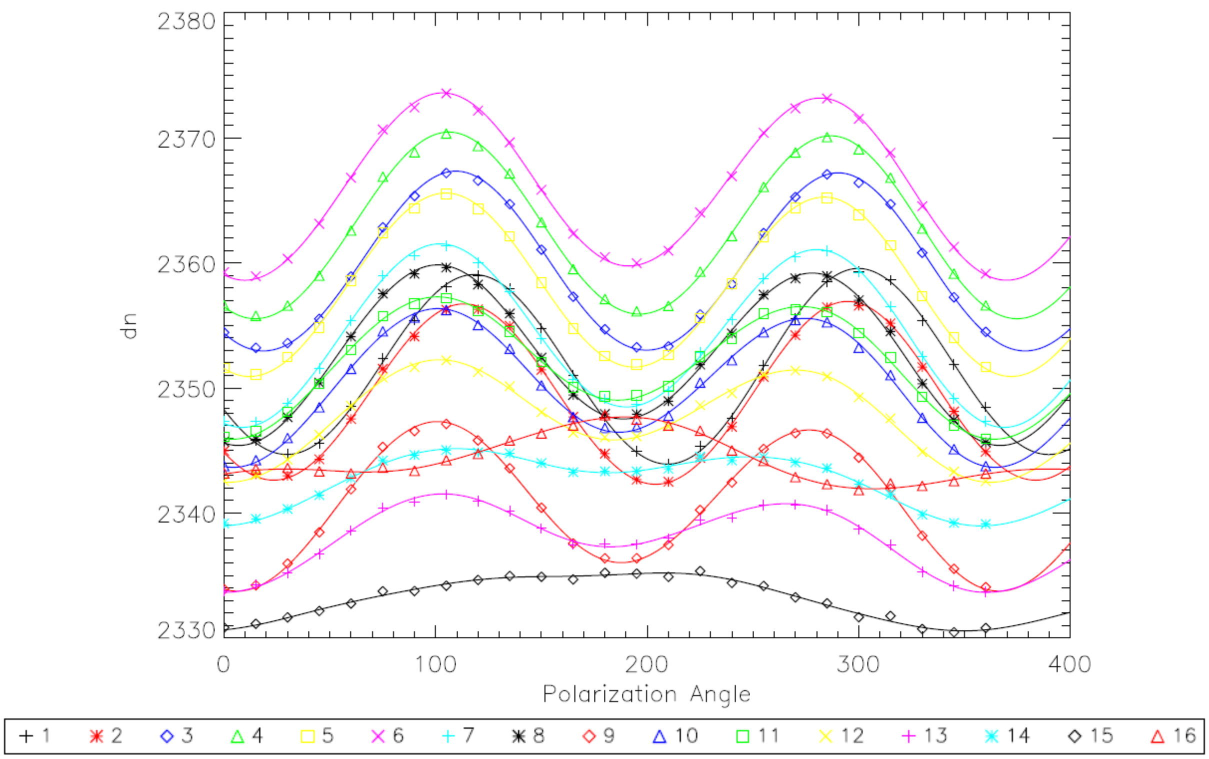

Figure 12: Fourier coefficients for M7 HAM A using BVONIR without the Sonoma filter

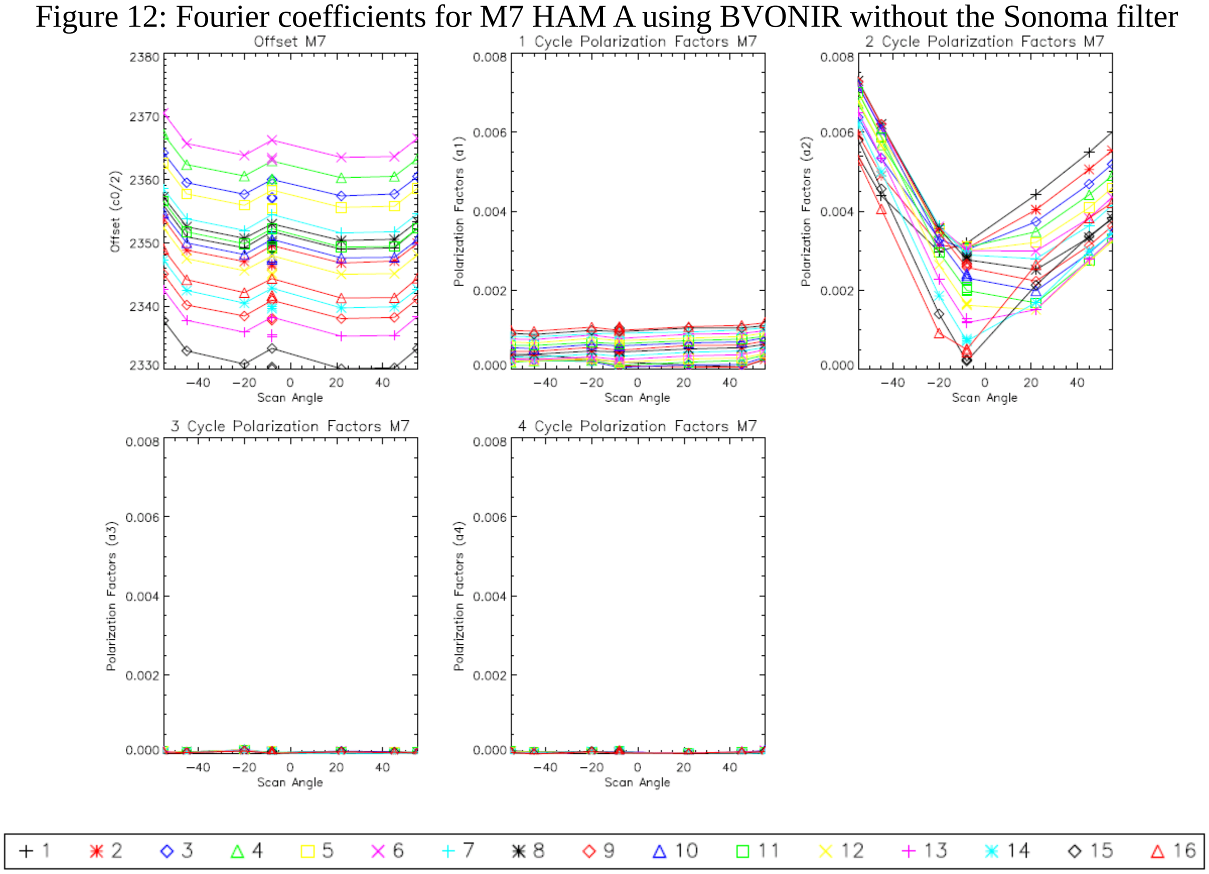

Figure 13: Polarization factor a_2 for M1, HAM side A in [%] across test configurations and repeated measurements

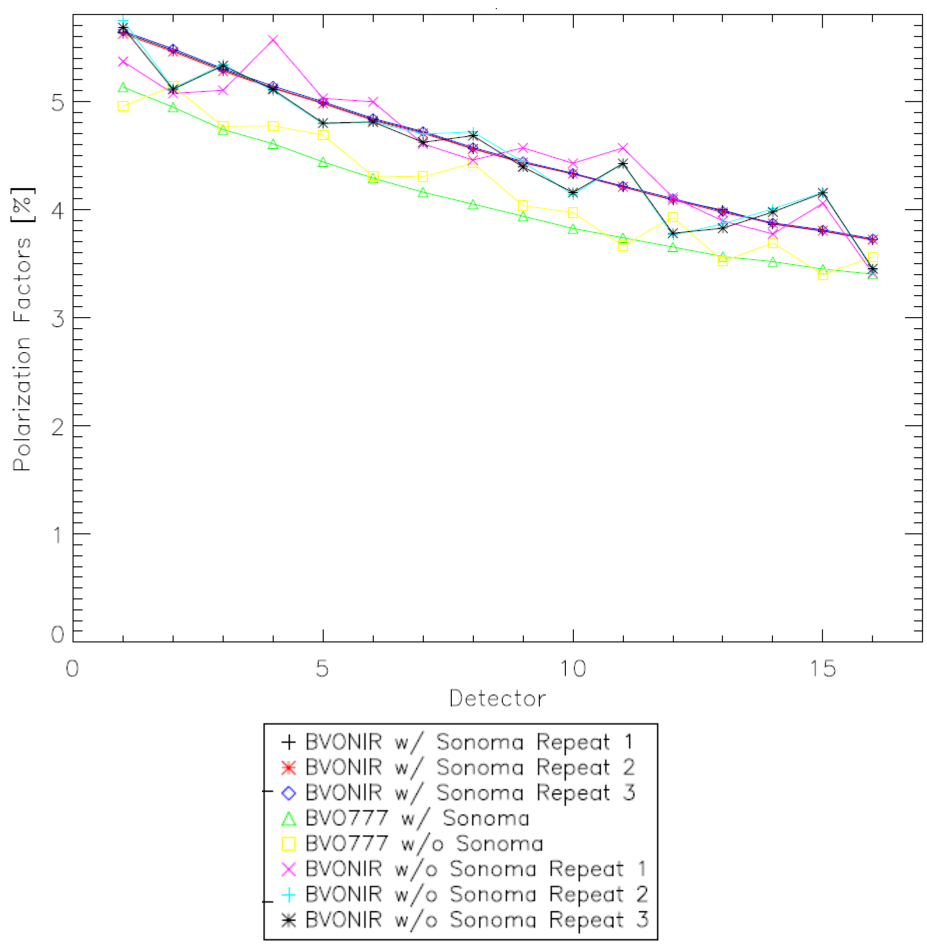

Figure 14: Polarization factor a_2 for HAM side A in [%] across scan angles

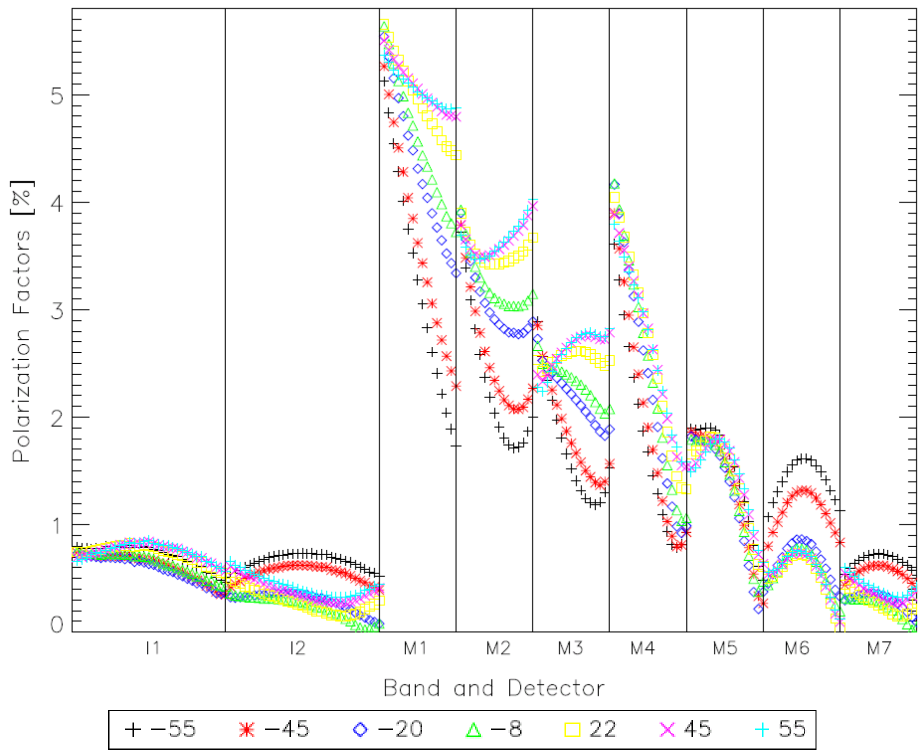

Figure 15: Polarization factor a_2 for HAM side B in [%] across scan angles

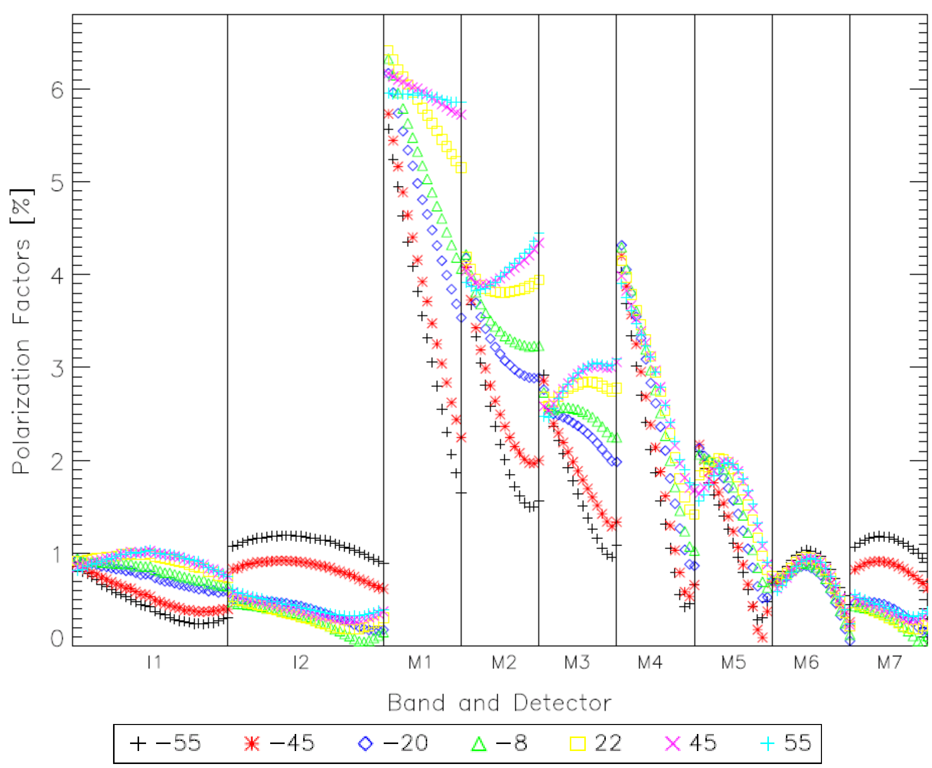

Figure 16: Polarization phase δ_2 for HAM side A in [%] across scan angles

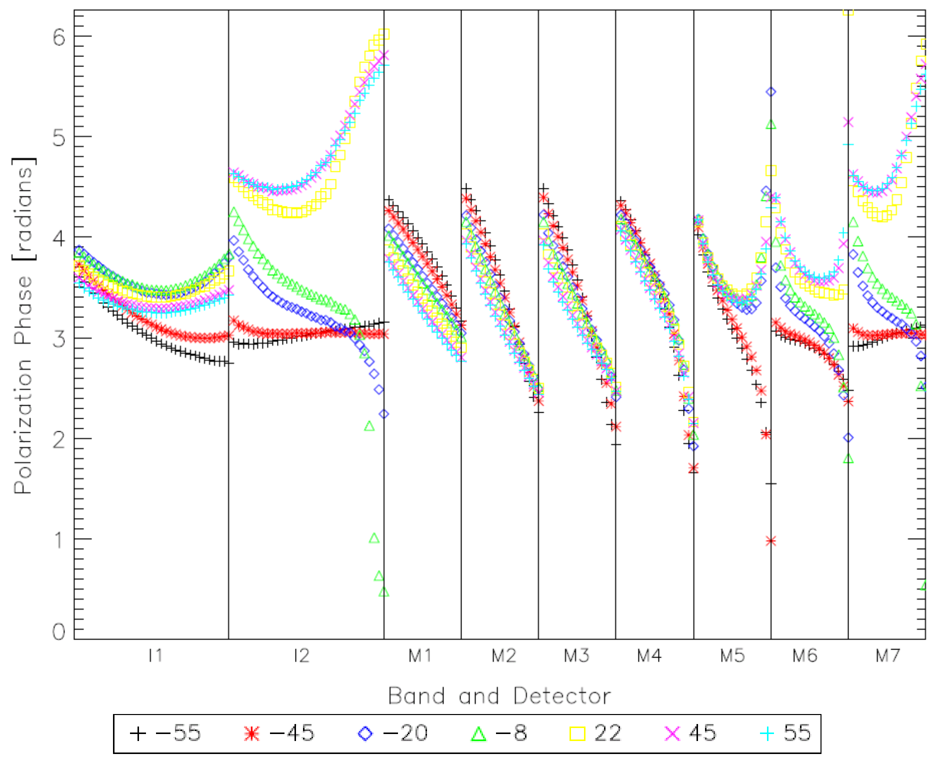

Figure 17: Polarization phase δ_2 for HAM side B in [%] across scan angles

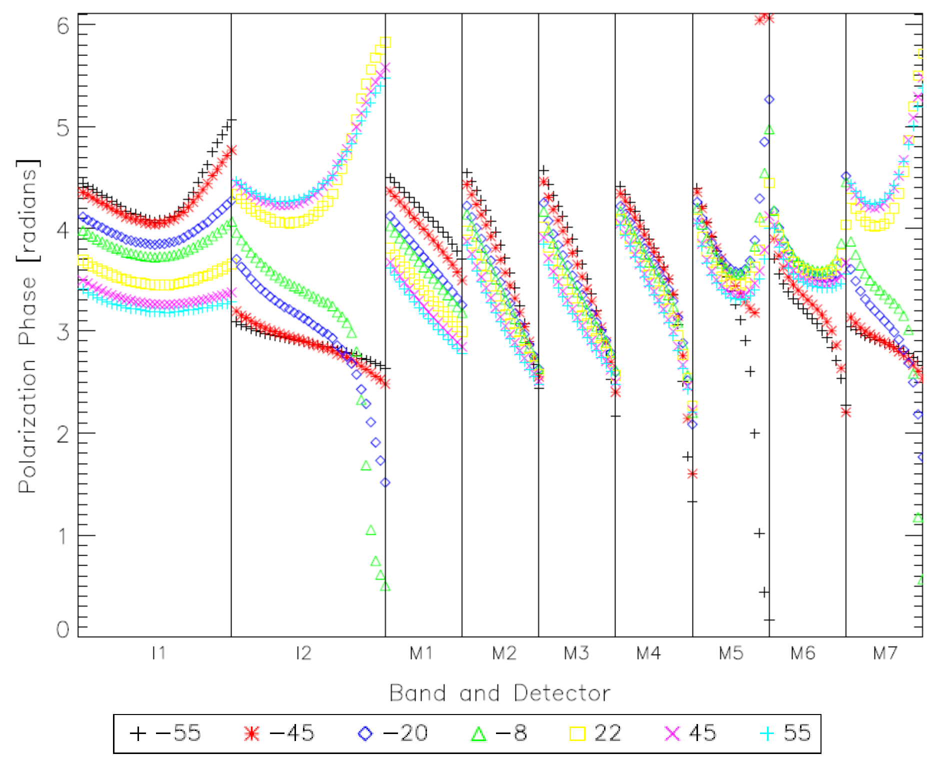

Figure 18: Comparison of polarization factors a_2 for HAM side A in [%] from nominal and special testing

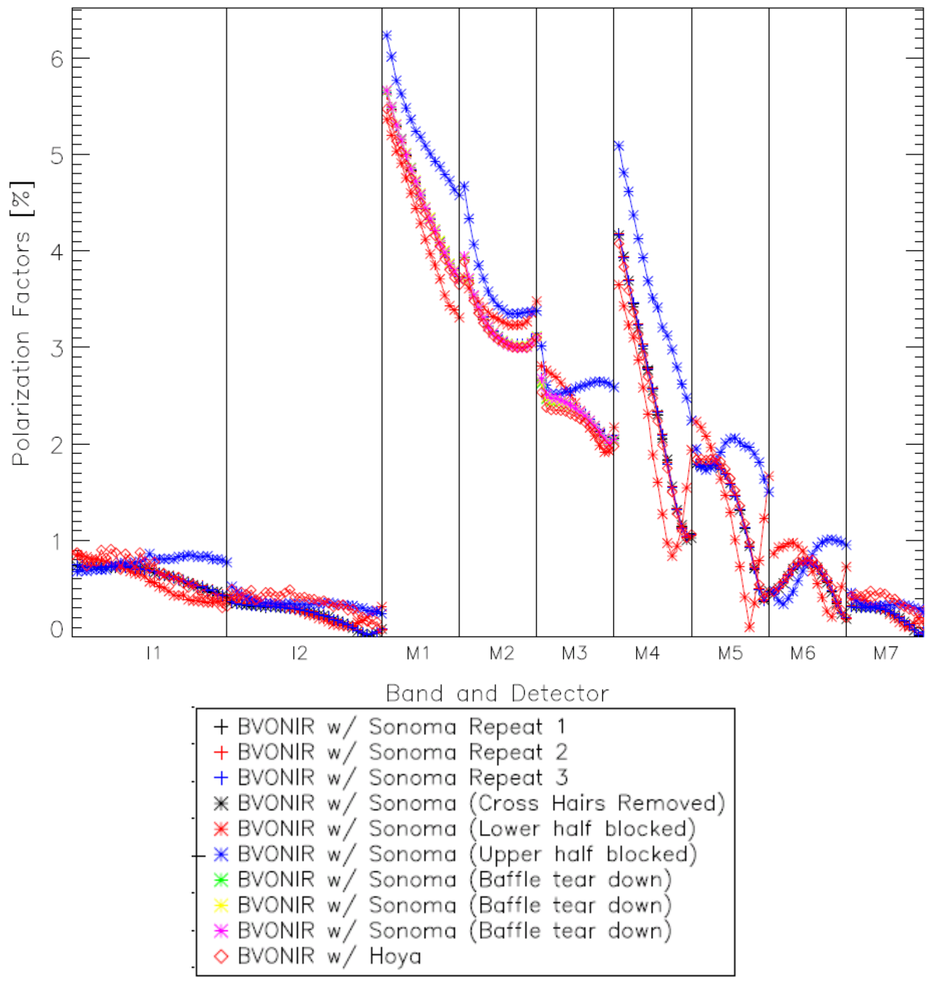

Figure 19: Difference between polarization factors a_2 for HAM side A in [%] between nominal testing and testing using the Hoya filter