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Polarization Properties of ACS

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ABSTRACT

The Advanced Camera for Surveys has two sets of polarizers optimized for the UV-blue (POL_UV) and the visible-red (POL_V). The polarization properties of the two polarizers, including the effects of the reflection from the third mirror in the optical train, have been computed for all the possible filters in both the Wide Field and High Resolution Cameras. Tables of the essential properties for polarization measurement of all the ACS filters are presented. The maximal differences in the polarization and the position angle, computed neglecting the polarization effects of the third mirror and assuming perfect polarizers, are tabulated. The tables provide a comparative assessment of the quality of the polarization measurements between the different filters. The data will be compared with ground-based and in-flight calibrations to refine the polarization properties, especially for the most popular filters.

Introduction

Of the three cameras in the Advanced Camera for Surveys (ACS), two can be used for measurements of linear polarization: the Wide Field Channel (WFC) and the High Resolution Channel (HRC). There are two sets of polarizing filters - a visible range polarizer (POLnV, where n is 0, 60 or 120 degrees) in filter wheel #2 and a UV-visible polarizer POLnUV in filter wheel #1. Both use dichroic film polarizers sandwiched between fused silica. Although the polarizers are dimensioned to cover the HRC field of view (26x29 arcsec), they can both be used for the WFC, where the unvignetted field is 72x72 arcsec. The transmission of light as a function of wavelength, and thus the range over which linear polarization can be measured, for incident radition oriented parallel and perpendicular to the axis of the polarizers is shown in Figure 1 for both polarizers. The transmission values

are also listed in Tables 11 and 12. The tabulated and plotted values are the average over the three polarizer filters (0, 60 and 120 degree orientation). The rejection (ratio of transmission of parallel and perpendicular components) is high (>10^3) for the V polarizer except at the longest wavelengths (>7500A) ; for the UV polarizer the rejection is about 100 times lower (see Figure 5.1 in the ACS Instrument Handbook, Jedrzejewski et al. 2000). Since there are two filter wheels with one set of polarizers in each wheel, the colour filters which can be used with the polarizers must be in the alternate filter wheel (see Figures 3.1 and 3.2 and Tables 4.1, 4.2 and 5.1 in the ACS Instrument Handbook, Jedrzejewski et al. 2000). Table 1 lists all the filters available with each polarizer.

If there were no other elements in the optical train of ACS which could induce some significant polarization, then the data in tables 11 and 12 would be all that is required to exactly determine the polarization from a set of measurements with the 0, 60 and 120 degree polarizers. See the ACS Instrument Handbook, Chapter 5 (Jedrzejewski et al. 2000) for an example of how to derive the polarization and position angle from the set of three measurements. However both the WFC and HRC have reflection optics, with the third mirror reflecting the input beam at about 45 degrees. At such an angle of incidence, the effect of a metallic mirror with an overcoating can have a substantial effect on the measured polarization. The reflection has the effect of inducing some circular polarization for incident linearly polarized light; since the ACS polarizers are not sensitive to circularly polarized light then the measured linear polarization and position angle can be in error. How large the error is depends on the source polarization and position angle and the wavelength at which it is measured, since the optical properties of the metallic mirrors vary with wavelength. It is the aim of this ISR to investigate these effects, determine how important they are and recommend the necessary data to correct these effects.
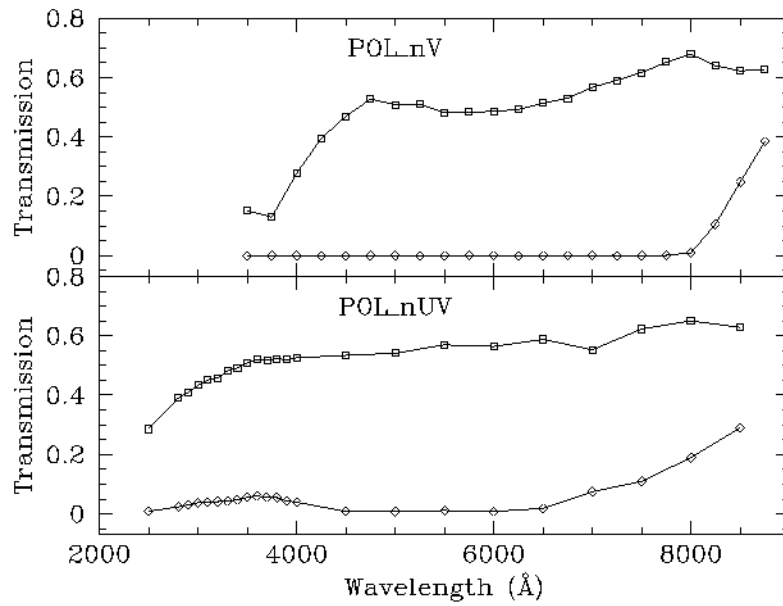
Figure 1: Plot of the transmission of the parallel (squares) and perpendicular (diamonds) components of incident radiation for the two ACS polarizers.

Table 1. Allowed combination of ACS polarizer and colour filters

POL_UV WFC	POL_UV HRC	POL_V WFC	POL_V HRC
CLEAR2L	CLEAR2S	CLEAR1L	CLEAR1S
F435W	F220W	F475W	F475W
F660N	F250W	F502N	F502N
F814W	F330W	F550M	F550M
	F344N	F555W	F555W
	F435W	F606W	F606W
	F660N	F625W	F625W
	F814W	F658N	F658N
		F775W	F775W
		F850LP	F850LP
		F892N*	F892N*

* Beyond useful range of polarizer

ACS Instrumental Parameters

Table 2 summarizes the surface shape, angle of incidence, metallic coating, overcoating material and deposited thickness for the three mirrors in both the WFC and HRC modes. All the data comes from Ball System Engineering Reports. The overcoating for the silvered WFC mirrors is a proprietary coating from Denton Vacuum Inc.

Table 2. Parameters of ACS mirrors

Camera	Mirror	Form	Incident angle (deg.)	Coating	Overcoating	Overcoating thickness (A)
WFC	IM1	Sphere	2.46	Ag	Denton	9600*
	IM2	Asphere	5.79	Ag	Denton	9600*
	IM3	Schmidt	49.6	Ag	Denton	9600
HRC	M1	Sphere	1.52	Al	Mag. Fluor.	247
	M2	Asphere	3.16	Al	Mag. Fluor.	242
	M3	Flat	47.9	Al	Mag. Fluor.	606

* Exact value not known. Assumed same as for IM3.

The induced polarization is largest for mirrors with the largest incidence angles so it is clear from Table 2 that the IM3 and M3 mirrors will have the greatest effect. The polarization properties of metallic mirros with overcoating can be treated by Maxwells' equations. Biretta and McMaster (1997) treated the case of the WFPC2 pick-off mirror and the same nomenclature is followed here. The two effects to be treated are the differing reflectivities for the two components of the electric vector (diattenuation) and the conversion of linear polarization to circular polarization by retardance of one component relative to another (circular retardance, e.g. Chipman 1992). In order to calculate the S wave (electric vector parallel to the surface) and P wave (electric vector perpendicular to the surface) reflectivities, the data required are the refractive indices of both the metallic film (real and imaginery parts) and the overcoating (real part), see Born and Wolf (1985) . For the metallic coatings the relevant data can be found in the AIP Handbook (1972), Table 6g. For Magnesium Fluoride, Dodge (1984) lists the real refractive index, and the value for the O ray was used (c.f. Biretta & McMaster 1997). However the Denton overcoat is proprietary and no refractive index data are available. This is a multi-layer coating so a single material refractive index value cannot be specified. However there are measurements of the S and P wave reflectivities in Woodruff (1996) as a function of wavelength. These are plotted in Figure 2.
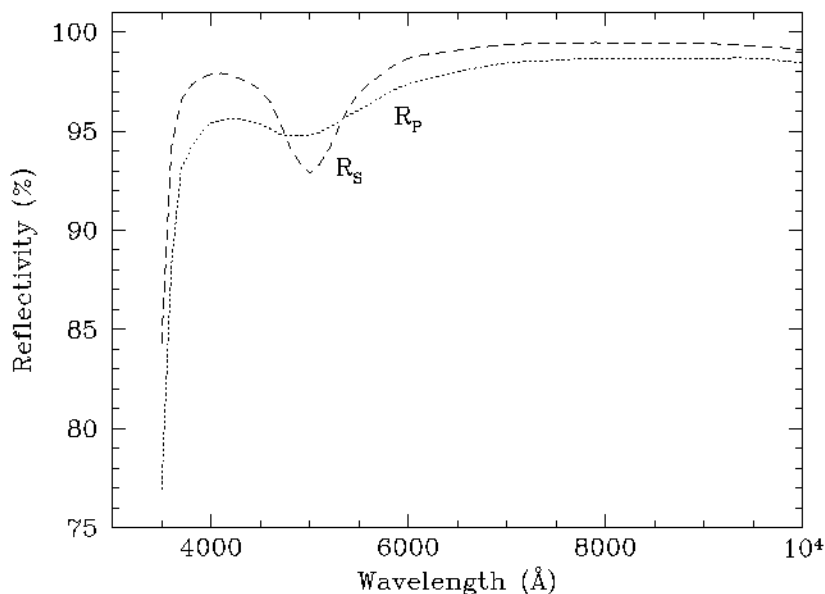

Figure 2: Variation of the observed S and P wave reflectivity of the ACS WFC IM3 mirror with wavelength for 49.6 degree angle of incidence (from Woodruff 1996)

Calculation of the S and P wave reflectivities (R_S and R_P) and the circular retardance as a function of wavelength for the HRC M3 mirror is similar to that for WFPC2 (Biretta & McMaster 1997). The circular retardance is measured by the phase of the s-wave relative to the p-wave (Delta Phi). Whilst the measured R_S and R_P values could be used for the WFC IM3 mirror diattenuation, the circular retardance cannot be determined without knowledge of the refractive index. Hueser (1996) presented a solution for the refractive index of the middle layer of the Denton overcoat for another mirror, not that in ACS, using an optimization code to derive the refractive index (real part n, imaginary part k) from the measured reflectivity of the mirror. A similar procedure was followed whereby the value of the real part of the refractive index was determined which locally minimized the match to the values of both R_S and R_P. The imaginary part of the refractive index, k, was set to zero. Figure 3 shows the observed and fitted values of R_S and R_P together with the derived refractive index. The fit is good except around 4000A and above 9500A for R_P. The refractive index values change in an errant way with wavelength but this was also found by Hueser (1996).
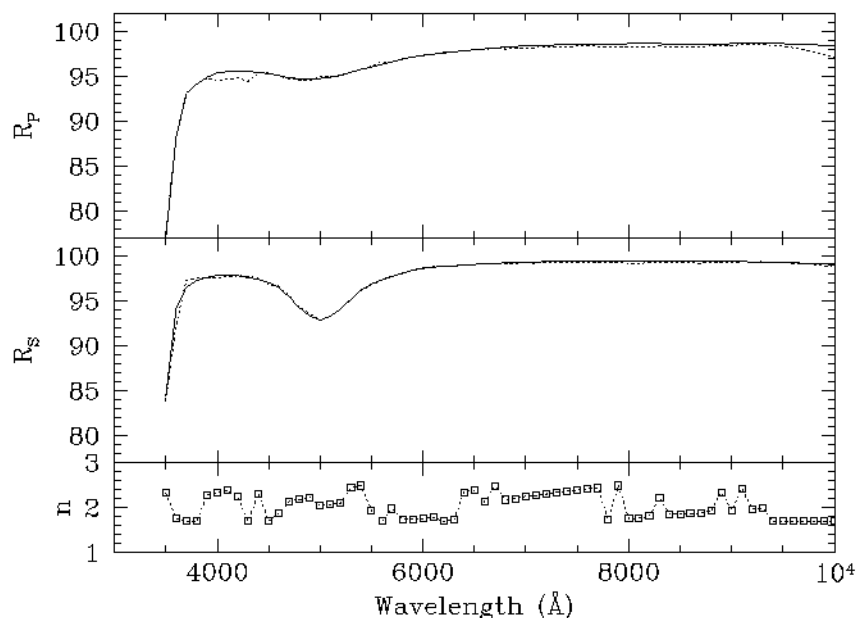
Figure 3: The observed (continuous line) and fitted (dotted line) P (upper panel) and S (middle panel) wave reflectivities for the WFC IM3 mirror at 49.6 degrees angle of incidence. The bottom panel shows the fitted real part (n) of the refractive index of the Denton overcoat.

Filter-Polarizer Parameters

Using the transmissions of the polarizers for radiation oriented parallel and perpendicular to the polarizer axis (Tables 7 and 8) and the transmissions of the instrument+filter combination, the polarizer transmission averged over the filter passband can be derived by integration. The assumption here is that the input spectrum is flat in F_{lambda} units. The instrument+filter passband was determined by multiplying the OTA, instrumental and filter transmissions and the detector DQE. The transmissions and DQE values were taken from the most recent files in the CDBS database. Similarly the S and P wave reflectivities resulting from the third mirror can also be integrated over the instrument+filter passband to determine the resulting diattenuation for each filter-polarizer combination. The circular retardance averaged over the filter passband can be similarly computed. Tables 3-6 tabu-

late the resultant polarization dependent parameters for all the allowed polarizer (POL_nUV and POL_nV) and colour filter combinations. for both the WFC and HRC. The first and second mirrors (the sphere and asphere respectively), which provide the correction of the spherical aberration, are employed at small angles of incidence. The diattenuation and circular retardance are very small (typically less than 0.1% diattenuation and 0.1 degrees in circular retardance) and so will be ignored at present.

Table 3. Polarization parameters for WFC POL_nUV.

Filter	T_{PARA}	T_{PERP}	R_S	R_P	Delta Phi
CLEAR2L	0.572	0.0556	0.970	0.945	172.43
F435W	0.532	0.0215	0.971	0.948	170.21
F660N	0.582	0.0284	0.992	0.981	186.44
F814W	0.623	0.156	0.993	0.984	182.64

Table 4. Polarization parameters for HRC POL_nUV

Filter	T_{PARA}	T_{PERP}	R_S	R_P	Delta Phi
CLEAR2S	0.569	0.0559	0.901	0.859	155.37
F220W	0.535	0.0510	0.937	0.895	182.88
F250W	0.521	0.0533	0.897	0.880	184.88
F330W	0.517	0.0586	0.861	0.873	169.21
F344N	0.522	0.0487	0.859	0.873	166.53
F435W	0.531	0.0236	0.887	0.882	149.88
F660N	0.582	0.0284	0.902	0.848	147.59
F814W	0.624	0.156	0.890	0.813	150.60

Table 5. Polarization parameters for WFC POL_nV

Filter	T_{PARA}	T_{PERP}	R_S	R_P	Delta Phi
CLEAR1L	0.510	0.0180	0.970	0.945	172.43
F475W	0.470	0.00154	0.957	0.950	160.68
F502N	0.508	0.000468	0.929	0.950	141.10
F550M	0.486	0.000386	0.971	0.964	151.93
F555W	0.499	0.000523	0.957	0.958	145.84
F606W	0.508	0.000390	0.973	0.968	162.07
F625W	0.507	0.000253	0.988	0.976	169.15
F658N	0.519	0.000319	0.991	0.980	187.22
F775W	0.627	0.0346	0.993	0.983	184.56
F850LP	0.627	0.253	0.991	0.978	178.41

Table 6. Polarization parameters for HRC POL_nV

Filter	T_{PARA}	T_{PERP}	R_S	R_P	Delta Phi
CLEAR1S	0.494	0.0176	0.901	0.858	155.37
F475W	0.470	0.00151	0.893	0.876	146.76
F502N	0.508	0.000468	0.891	0.866	145.17
F550M	0.486	0.000388	0.900	0.863	145.13
F555W	0.499	0.000528	0.898	0.866	145.22
F606W	0.508	0.000401	0.899	0.857	146.11
F625W	0.507	0.000253	0.901	0.852	146.64
F658N	0.519	0.000323	0.902	0.848	147.35
F775W	0.627	0.0349	0.881	0.802	149.36
F850LP	0.627	0.254	0.920	0.857	153.27

The data in Tables 3-6 have been included in files for use by the `iraf.stecf.impol` package (Version 2.0) for simulating and computing polarization for the ACS. This package allows simulation of the measured signal in each polarizer (0, 60 and 120 degrees) image for given input polarization and total (Stokes I) signal, as well as calculation of the polarization (either as images or in apertures) from sets of images. The data in Tables 3-6 are obviously preliminary until ground and in-flight polarization calibration data is analysed.

Observed polarization and position angle

The net effect of the less than perfect polarizers and the large angle reflection of the third mirror in the ACS is that the derived polarization and position angle would not exactly match the values for a source with known input, compared with a perfect polarizer and no reflections. This effect depends on the camera and filter used, and the input polarization and position angle values, so cannot generally be specified. However it is interesting to show the magnitude of this effect. Simulations for a uniform polarized source with constant position angle were made for each filter and the three sets of 0, 60 and 120 degree images using the above sets of filter polarization parameters (Tables 3-6) and the `iraf.stecf.impol` package. The three images were then analysed with the instrument roll angle stepped every 5 degrees from 0 to 180 degrees but without any diattenuation and retardance (i.e. R_S=1.0, R_P=1.0 Delta Phi=0.0) and for a pefect polarizer (T_{PARA}=1.0, T_{PERP}=0.0). The typical behaviour of the observed polarization and position angle is shown in Figure 4 for the WFC, POL_nV and F625W filter. This was based on a simulation for a very bright source (i.e. negligable errors) with linear polarization of 10% and polarization position angle 33 degrees.

Tables 7-10 list, for each polarizer, the largest discrepancy over the 37 determinations from the measured polarization of 10%, first neglecting the effects of diattenuation and retardance (column 2), then assuming, in addition, a perfect polarizer (column 3). The difference in the measured and known polarization, for the case of neglect of diattenuation, scales linearly with the polarization; thus for the case of POL_nV and F625W for the WFC, a 30% polarized source would yield a polarization of 31.4% for a position angle of 120 degrees. The largest difference in measured position angle (resulting from neglect of the retardance) is listed in column 4 of the tables. These tables give an indication of the size of the effects involved. Given the uncertainties on the properties of the Denton overcoat, tables 7 and 9 for the WFC should be taken as indicative until calibration data are available.
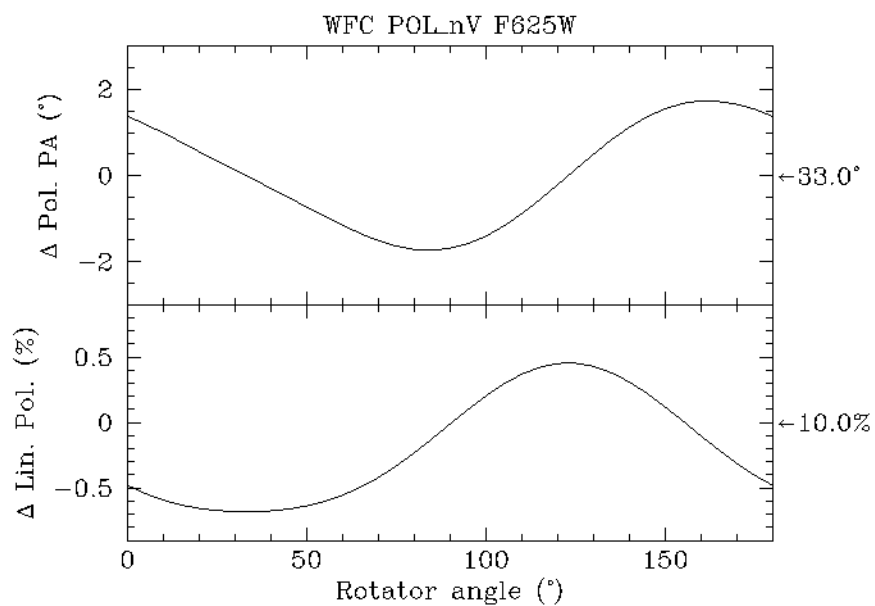
Figure 4: Behaviour of the measured linear polarization and position angle for WFC with the V polarizer and the F625W filter, if the diattenuation of the IM3 mirror is ignored and the polarizer is asumed to be perfect.

Table 7. Difference in measured - expected linear polarization (source with 10% linear polarization) and position angle neglecting the effect of IM3 and non-perfect polarizer for the WFC and POL_nUV.

Filter	Delta Pol. Diattenuation (%)	Delta Pol. Perfect Polarizer (%)	Delta PA (degrees)
CLEAR2L	5.36	2.91	3.81
F435W	1.29	1.97	3.51
F660N	0.64	1.51	1.61
F814W	0.53	4.32	1.33

Table 8. Difference in measured - expected linear polarization (source with 10% linear polarization) and position angle neglecting the effect of M3 and non-perfect polarizer for the HRC and POL_nUV.

Filter	Delta Pol. Diattenuation (%)	Delta Pol. Perfect Polarizer (%)	Delta PA (degrees)
CLEAR2S	6.74	3.80	7.40
F220W	2.33	3.67	6.56
F250W	1.10	2.75	2.89
F330W	0.76	2.64	1.94
F344N	0.88	2.43	2.36
F435W	1.46	2.19	2.60
F660N	3.13	3.77	10.09
F814W	4.53	6.72	13.97

Table 9. Difference in measured - expected linear polarization (source with 10% linear polarization) and position angle neglecting the effect of IM3 and non-perfect polarizer for the WFC and POL_nV

Filter	Delta Pol. Diattenuation (%)	Delta Pol. Perfect Polarizer (%)	Delta PA (degrees)
CLEAR1L	14.49	1.99	3.81
F475W	0.73	0.74	1.61
F502N	2.45	2.43	6.06
F550M	1.31	1.31	2.64
F555W	1.82	1.82	2.76
F606W	0.63	0.63	1.33
F625W	0.68	0.68	1.74
F658N	0.67	0.67	1.64
F775W	0.56	1.55	1.38
F850LP	0.68	6.03	1.79

Table 10. Difference in measured - expected linear polarization (source with 10% linear polarization) and position angle neglecting the effect of M3 and non-perfect polarizer for the HRC and POL_nV.

Filter	Delta Pol. Diattenuation (%)	Delta Pol. Perfect Polarizer (%)	Delta PA (degrees)
CLEAR1S	16.79	2.98	7.40
F475W	1.87	1.88	4.73
F502N	2.17	2.17	6.24
F550M	2.44	2.44	7.74
F555W	2.30	2.31	7.04
F606W	2.58	2.58	8.44
F625W	2.89	2.89	9.44
F658N	3.13	3.13	10.07
F775W	4.69	5.25	14.54
F850LP	3.58	7.28	10.92

Comparison among tables 7-10 shows the following results:

1. The higher rejection of the light perpendicular to the optical axis for the V polarizer (POL_nV), compared to the UV (POL_nUV) polarizer (Figure 1 and Tables 11 and 12), results in performance much closer to that of a "perfect" polarizer. However below 4500A and above 8000A, there is a marked departure from the "perfect" polarizer case for the V polarizer.

2. The IM3 mirror of the WFC has lower diattenuation compared to that of the M3 mirror of the HRC for the same filter.

3. The retardance of the WFC IM3 mirror is lower than for the HRC M3 mirror for the same filter.

4. The CLEAR filters all have large diattenuation effects. Since the passband is so large the actual effect will depend on the spectral energy distribution of the source, since different wavelengths contribute differing amounts to the diattenuation. For the most accurate determination of the polarization parameters with the wide (W) and CLEAR filters, the spectrum of the source is required to re-compute the values in Tables 3-6.

5. Using the UV polarizer in the red or the V polarizer in the blue results in large diattenuation and retardance.

6. The larger the diattenuation effect in tables 7-10, the larger will be the uncertainty in completely compensating for the effect since the properties of the mirror coatings (mainly coating layer thickness, refractive index) are not exactly known.

The effect of the first and second mirrors in the ACS optical train (i.e. IM1 and IM2 for the WFC and M1 and M2 for the HRC, see Table 2) on the measured polarization is extremely small. The largest effect is for IM2 which has an angle of incidence of 5.8 degrees. The effect of neglecting the diattenuation of this mirror results in a maximum possible error of 0.12% in linear polarization and 0.03 degrees in position angle.

Conclusions

Based on manufacturer's data, and or test data taken at Ball Aerospace during the construction of the ACS, the polarization properties of the two polarizers - POL_UV and POL_V, including the effects of the reflection from the last mirror in the optical train, have been computed for all the possible filters in both the Wide Field and High Resolution Cameras. Tables of the essential properties for polarization measurement of all the filters are presented, including the errors made in neglecting the effects of the mirror reflections and the non-perfect polarizers. These data will be compared with ground-based and in-flight calibrations to refine the polarization properties, especially for the most popular filters. Not all the possible polarizer-filter combinations will be offered as fully supported modes with calibration data; Table 5.1 of Jedrzejewski et al (2000) lists those filters which are expected to be offered.

The polarization properties in Tables 3-6 are available as `stsdas` table files for use in the `iraf.stecf.impol` package for simulating polarization observations with ACS.

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Table 11. Parallel and perpendicular components of average transmission of ACS POL_UV polarizer.

Lambda (A)	Trans PAR	Trans PERP
2500	0.286	0.0077
2800	0.391	0.024
2900	0.410	0.030
3000	0.433	0.037
3100	0.451	0.039
3200	0.458	0.041
3300	0.482	0.043
3400	0.492	0.048
3500	0.509	0.056
3600	0.520	0.060
3700	0.518	0.056
3800	0.523	0.055
3900	0.520	0.043
4000	0.526	0.039
4500	0.534	0.0082
5000	0.541	0.0085
5500	0.569	0.011
6000	0.564	0.0079
6500	0.588	0.019
7000	0.553	0.075
7500	0.623	0.011
8000	0.650	0.019
8500	0.628	0.029

Table 12. Parallel and perpendicular components of average transmission of ACS POL_V polarizer.

Lambda (A)	Trans PAR	Trans PERP
3500	0.152	0.000074
3750	0.130	0.00019
4000	0.277	0.00030
4250	0.395	0.00029
4500	0.569	0.00020
4750	0.527	0.00017
5000	0.509	0.000052
5250	0.511	0.000044
5500	0.482	0.000041
5750	0.485	0.000033
6000	0.486	0.000028
6250	0.493	0.000025
6500	0.514	0.000024
6750	0.530	0.000022
7000	0.568	0.000024
7250	0.591	0.000018
7500	0.617	0.000039
7750	0.652	0.00069
8000	0.678	0.0090
8250	0.640	0.106
8500	0.622	0.249
8750	0.628	0.385