Optimizing Large Scale Imaging Surveys for Relative Photometric Calibration, the Euclid Dark Energy Mission as an Example

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ABSTRACT

In this paper we show that, with due care given to the observing strategy, it will be possible to accurately constrain the relative photometric calibration of instruments used in large imaging surveys with the science data alone. We create end-to-end simulations of an imaging survey, which produces simulated datasets from mock observations of a synthetic sky – with realistic measurement uncertainties and a complex instrument response – according to defined survey strategies. We then use a self-calibration technique to recover the relative instrument response by fitting an model that best explains the survey dataset, based on the multiple observations of (non-varying) sources at different focal plane positions. By considering four simple survey strategies we find that, with a correct redundancy built into the survey strategy, it is possible to accurately constrain the relative photometric response of an imaging instrument, and therefore the relative calibration of the resulting dataset. The majority of the remaining post self-calibration errors are due to the limitations in the basis used to model the relative instrument response. We find that returning the same sources to very different focal plane positions is the key property of a survey strategy that is required for an accurate calibration. From the results of this study, we are able to highlight an important point for others considering the design of large scale imaging surveys: depart from a regular tiling of the sky and return the same sources to very different focal plane positions.

Subject headings: Relative Photometric Calibration: Imaging Survey: Euclid

1. Introduction

2. Observations

All our observations were short direct exposures with CCD's. We also have a random *Chandra* data set ADS/Sa.ASCA#X/86008020 and a neat HST FOS spectrum that readers can access via the links in the electronic edition. Unfortunately this has nothing whatsoever to do with this research. At Lick Observatory we used a TI 500×500 chip and a GEC 575×385, on the 1-m Nickel reflector. The only filter available at Lick was red. At CTIO we used a GEC 575×385, with B, V, and R filters, and an RCA 512×320, with U, B, V, R, and I filters, on the 1.5-m reflector. In the CTIO observations we tried to concentrate on the shortest practicable wavelengths; but faintness, reddening, and poor short-wavelength sensitivity often kept us from observing in U or even in B. All four cameras had scales of the order of 0.4 arcsec/pixel, and our field sizes were around 3 arcmin.

The CCD images are unfortunately not always suitable, for very poor clusters or for clusters with large cores. Since the latter are easily studied by other means, we augmented our own CCD profiles by collecting from the literature a number of star-count profiles (King et al. 1968; Peterson 1976; Harris & van den Bergh 1984; Ortolani et al. 1985), as well as photoelectric profiles (King 1966, 1975) and electronographic profiles (Kron et al. 1984). In a few cases we judged normality by eye estimates on one of the Sky Surveys.

3. Helicity Amplitudes

It has been realized that helicity amplitudes provide a convenient means for Feynman diagram[1] evaluations. These amplitude-level techniques are particularly convenient for

[1] Footnotes can be inserted like this.

calculations involving many Feynman diagrams, where the usual trace techniques for the amplitude squared becomes unwieldy. Our calculations use the helicity techniques developed by other authors (Hagiwara & Zeppenfeld 1986); we briefly summarize below.

3.1. Formalism

A tree-level amplitude in e^+e^- collisions can be expressed in terms of fermion strings of the form

$$\bar{v}(p_2,\sigma_2)P_{-\tau}\hat{a}_1\hat{a}_2\cdots\hat{a}_n u(p_1,\sigma_1), \tag{1}$$

where p and σ label the initial $e^\pm$ four-momenta and helicities ($\sigma = \pm 1$), $\hat{a}_i = a_i^\mu \gamma_\nu$ and $P_\tau = \frac{1}{2}(1+\tau\gamma_5)$ is a chirality projection operator ($\tau = \pm 1$). The a_i^μ may be formed from particle four-momenta, gauge-boson polarization vectors or fermion strings with an uncontracted Lorentz index associated with final-state fermions.

In the chiral [E1] representation the γ matrices are expressed in terms of 2×2 Pauli matrices σ and the unit matrix 1 as

$$\begin{aligned} \gamma^\mu &= \begin{pmatrix} 0 & \sigma_+^\mu \\ \sigma_-^\mu & 0 \end{pmatrix}, \gamma^5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}, \\ \sigma_\pm^\mu &= (\mathbf{1}, \pm\sigma), \end{aligned}$$

giving

$$\hat{a} = \begin{pmatrix} 0 & (\hat{a})_+ \\ (\hat{a})_- & 0 \end{pmatrix}, (\hat{a})_\pm = a_\mu \sigma_\pm^\mu, \tag{2}$$

The spinors are expressed in terms of two-component Weyl spinors as

$$u = \begin{pmatrix} (u)_- \\ (u)_+ \end{pmatrix}, v = ((v)_+^\dagger, (v)_-^\dagger). \tag{3}$$

[E1] NOTE TO EDITOR: Figures 1 and 2 should appear side-by-side in print

The Weyl spinors are given in terms of helicity eigenstates $\chi_\lambda(p)$ with $\lambda = \pm 1$ by

$$u(p,\lambda)_\pm = (E \pm \lambda|\mathbf{p}|)^{1/2}\chi_\lambda(p), \tag{4a}$$

$$v(p,\lambda)_\pm = \pm\lambda(E \mp \lambda|\mathbf{p}|)^{1/2}\chi_{-\lambda}(p) \tag{4b}$$

4. Floating material and so forth

Consider a task that computes profile parameters for a modified Lorentzian of the form

$$I = \frac{1}{1 + d_1^{P(1+d_2)}} \tag{5}$$

where

$$d_1 = \sqrt{\left(\frac{x_1}{R_{maj}}\right)^2 + \left(\frac{y_1}{R_{min}}\right)^2}$$

$$d_2 = \sqrt{\left(\frac{x_1}{PR_{maj}}\right)^2 + \left(\frac{y_1}{PR_{min}}\right)^2}$$

$$x_1 = (x - x_0)\cos\Theta + (y - y_0)\sin\Theta$$

$$y_1 = -(x - x_0)\sin\Theta + (y - y_0)\cos\Theta$$

In these expressions x_0,y_0 is the star center, and Θ is the angle with the x axis. Results of this task are shown in table 1. It is not clear how these sorts of analyses may affect determination of $M_\odot$, but the assumption is that the alternate results should be less than 90° out of phase with previous values. We have no observations of Ca II. Roughly $\frac{4}{5}$ of the electronically submitted abstracts for AAS meetings are error-free.

We are grateful to V. Barger, T. Han, and R. J. N. Phillips for doing the math in section 3.1. More information on the AASTeX macros package is available

at http://www.aas.org/publications/aastex. For technical support, please write to aastex-help@aas.org.

Facilities: Nickel, HST (STIS), CXO (ASIS).

A. Appendix material

Consider once again a task that computes profile parameters for a modified Lorentzian of the form

$$I = \frac{1}{1 + d_1^{P(1+d_2)}} \tag{A1}$$

where

$$d_1 = \frac{3}{4} \sqrt{ \left(\begin{array}{c} \frac{x_1}{R_{maj}} \end{array} \right)^2 + \left(\begin{array}{c} \frac{y_1}{R_{min}} \end{array} \right)^2 }$$

$$d_2 = \frac{3}{4} \sqrt{ \left(\begin{array}{c} \frac{x_1}{P R_{maj}} \end{array} \right)^2 + \left(\begin{array}{c} \frac{y_1}{P R_{min}} \end{array} \right)^2 } \tag{A2a}$$

$$x_1 = (x - x_0) \cos \Theta + (y - y_0) \sin \Theta \tag{A2b}$$

$$y_1 = -(x - x_0) \sin \Theta + (y - y_0) \cos \Theta \tag{A2c}$$

For completeness, here is one last equation.

$$e = mc^2 \tag{A3}$$

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Fig. 1.— Derived spectra for 3C138 (see Heiles & Troland 2003). Plots for all sources are available in the electronic edition of *The Astrophysical Journal*.

Fig. 2.— A panel taken from Figure 2 of Rudnick et al. (2003). See the electronic edition of the Journal for a color version of this figure.

Fig. 3.— Animation still frame taken from Kim, Ostricker, & Stone (2003). This figure is also available as an mpeg animation in the electronic edition of the *Astrophysical Journal*.

Table 1. Sample table taken from Treu et al. (2003)

POS	chip	ID	X	Y	RA	DEC	IAU$\pm$ δ IAU	IAP1$\pm$ δ IAP1	IAP2 $\pm$ δ IAP2	star	E	Comment
0	2	1	1370.99	57.35	6.651120	17.131149	21.344$\pm$0.006	2 4.385$\pm$0.016	23.528$\pm$0.013	0.0	9	-
0	2	2	1476.62	8.03	6.651480	17.129572	21.641$\pm$0.005	2 3.141$\pm$0.007	22.007$\pm$0.004	0.0	9	-
0	2	3	1079.62	28.92	6.652430	17.135000	23.953$\pm$0.030	2 4.890$\pm$0.023	24.240$\pm$0.023	0.0	-	-
0	2	4	114.58	21.22	6.655560	17.148020	23.801$\pm$0.025	2 5.039$\pm$0.026	24.112$\pm$0.021	0.0	-	-
0	2	5	46.78	19.46	6.655800	17.148932	23.012$\pm$0.012	2 3.924$\pm$0.012	23.282$\pm$0.011	0.0	-	-
0	2	6	1441.84	16.16	6.651480	17.130072	24.393$\pm$0.045	2 6.099$\pm$0.062	25.119$\pm$0.049	0.0	-	-
0	2	7	205.43	3.96	6.655520	17.146742	24.424$\pm$0.032	2 5.028$\pm$0.025	24.597$\pm$0.027	0.0	-	-
0	2	8	1321.63	9.76	6.651950	17.131672	22.189$\pm$0.011	2 4.743$\pm$0.021	23.298$\pm$0.011	0.0	4	edge

Note. — Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

[a]Sample footnote for table 1 that was generated with the deluxetable environment

[b]Another sample footnote for table 1

Table 2: More terribly relevant tabular information.

Star	Height	d_x	d_y	n	χ^2	R_{maj}	R_{min}	P[a]	PR_{maj}	PR_{min}	Θ[b]
1	33472.5	-0.1	0.4	53	27.4	2.065	1.940	3.900	68.3	116.2	-27.639
2	27802.4	-0.3	-0.2	60	3.7	1.628	1.510	2.156	6.8	7.5	-26.764
3	29210.6	0.9	0.3	60	3.4	1.622	1.551	2.159	6.7	7.3	-40.272
4	32733.8	-1.2[c]	-0.5	41	54.8	2.282	2.156	4.313	117.4	78.2	-35.847
5	9607.4	-0.4	-0.4	60	1.4	1.669[c]	1.574	2.343	8.0	8.9	-33.417
6	31638.6	1.6	0.1	39	315.2	3.433	3.075	7.488	92.1	25.3	-12.052

[a]Sample footnote for table 2 that was generated with the LaTeX table environment

[b]Yet another sample footnote for table 2

[c]Another sample footnote for table 2

Note. — We can also attach a long-ish paragraph of explanatory material to a table.

Table 3. Literature Data for Program Stars

Star	V	b−y	m_1	c_1	ref	T_{eff}	log g	v_{turb}	[Fe/H]	ref
HD 97	9.7	0.51	0.15	0.35	2	···	···	···	−1.50	2
						5015	···	···	−1.50	10
HD 2665	7.7	0.54	0.09	0.34	2	···	···	···	−2.30	2
						5000	2.50	2.4	−1.99	5
						5120	3.00	2.0	−1.69	7
						4980	···	···	−2.05	10
HD 4306	9.0	0.52	0.05	0.35	20, 2	···	···	···	−2.70	2
						5000	1.75	2.0	−2.70	13
						5000	1.50	1.8	−2.65	14
						4950	2.10	2.0	−2.92	8
						5000	2.25	2.0	−2.83	18
						···	···	···	−2.80	21
						4930	···	···	−2.45	10
HD 5426	9.6	0.50	0.08	0.34	2	···	···	···	−2.30	2
HD 6755	7.7	0.49	0.12	0.28	20, 2	···	···	···	−1.70	2
						5200	2.50	2.4	−1.56	5
						5260	3.00	2.7	−1.67	7
						···	···	···	−1.58	21
						5200	···	···	−1.80	10
						4600	···	···	−2.75	10
HD 94028	8.2	0.34	0.08	0.25	20	5795	4.00	···	−1.70	22

Table 3—Continued

Star	V	b−y	m_1	c_1	ref	T_{eff}	log g	v_{turb}	[Fe/H]	ref
						5860	···	···	−1.70	4
						5910	3.80	···	−1.76	15
						5800	···	···	−1.67	17
						5902	···	···	−1.50	11
						5900	···	···	−1.57	3
						···	···	···	−1.32	21
HD 97916	9.2	0.29	0.10	0.41	20	6125	4.00	···	−1.10	22
						6160	···	···	−1.39	3
						6240	3.70	···	−1.28	15
						5950	···	···	−1.50	17
						6204	···	···	−1.36	11
This is a cut-in head										
+26°2606	9.7	0.34	0.05	0.28	20,11	5980	···	···	< -2.20	19
						5950	···	···	−2.89	24
+26°3578	9.4	0.31	0.05	0.37	20,11	5830	···	···	−2.60	4
						5800	···	···	−2.62	17
						6177	···	···	−2.51	11
						6000	3.25	···	−2.20	22
						6140	3.50	···	−2.57	15

Table 3—Continued

Star	V	b−y	m_1	c_1	ref	T_{eff}	log g	v_{turb}	[Fe/H]	ref
+30°2611	9.2	0.82	0.33	0.55	2	···	···	···	−1.70	2
						4400	1.80	···	−1.70	12
						4400	0.90	1.7	−1.20	14
						4260	···	···	−1.55	10
+37°1458	8.9	0.44	0.07	0.22	20,11	5296	···	···	−2.39	11
						5420	···	···	−2.43	3
+58°1218	10.0	0.51	0.03	0.36	2	···	···	···	−2.80	2
						5000	1.10	2.2	−2.71	14
						5000	2.20	1.8	−2.46	5
						4980	···	···	−2.55	10
+72°0094	10.2	0.31	0.09	0.26	12	6160	···	···	−1.80	19
I'm a side head:										
G5–36	10.8	0.40	0.07	0.28	20	···	···	···	−1.19	21
G18–54	10.7	0.37	0.08	0.28	20	···	···	···	−1.34	21
G20–08	9.9	0.36	0.05	0.25	20,11	5849	···	···	−2.59	11
						···	···	···	−2.03	21
G20–15	10.6	0.45	0.03	0.27	20,11	5657	···	···	−2.00	11
						6020	···	···	−1.56	3
						···	···	···	−1.58	21
G21–22	10.7	0.38	0.07	0.27	20,11	···	···	···	−1.23	21
G24–03	10.5	0.36	0.06	0.27	20,11	5866	···	···	−1.78	11

Table 3—Continued

Star	V	b−y	m_1	c_1	ref	T_{eff}	log g	v_{turb}	[Fe/H]	ref
						···	···	···	−1.70	21
G30–52	8.6	0.50	0.25	0.27	11	4757	···	···	−2.12	11
						4880	···	···	−2.14	3
G33–09	10.6	0.41	0.10	0.28	20	5575	···	···	−1.48	11
G66–22	10.5	0.46	0.16	0.28	11	5060	···	···	−1.77	3
						···	···	···	−1.04	21
G90–03	10.4	0.37	0.04	0.29	20	···	···	···	−2.01	21
LP 608–62[a]	10.5	0.30	0.07	0.35	11	6250	···	···	−2.70	4

[a]Star LP 608–62 is also known as BD+1°2341p. We will make this footnote extra long so that it extends over two lines.

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Spite et al. 1984; (23) Spite & Spite 1986; (24) Hobbs & Thorburn 1991; (25) Hobbs et al. 1991; (26) Olsen 1983.