APO Imager

(science background, goals and overview)

- History of science with SPIcam. Its usage and publications for the past 5 years.
- Filter usage for the past 5 years
- Compelling reasons to retire SPIcam
- Review of current design requirements
- Comparison of CCD choice with current APO imagers (SPIcam and AGILE)
- Potential science improvements with new imager

Seaver Prototype Imaging Camera
(SPIcam)

Developed and built by Engineering Group at UW (PI: C. Stubbs)[1]

Delivered to the 3.5-m, September 1997

SITe / TK2048E CCD, 2048x2048, 24μm pixels (similar to the Sloan Imager chips which were TK2048D)

Cooled with a Brooks Automation Polycold Compact Cooler (PCC or Cryotiger) to 163K (-110°C)

6 position filter wheel (4 copies) for large compliment of 3x3 inch^2 and 2x2 inch^2 broad and narrow bandpass filters (~200 total available in the on site catalog)

1.Thanks to the generous support of the Seaver Institute and the David and Lucille Packard Foundation who made construction of this instrument possible.

SPIcam Instrument Usage

(October 1 - September 30)

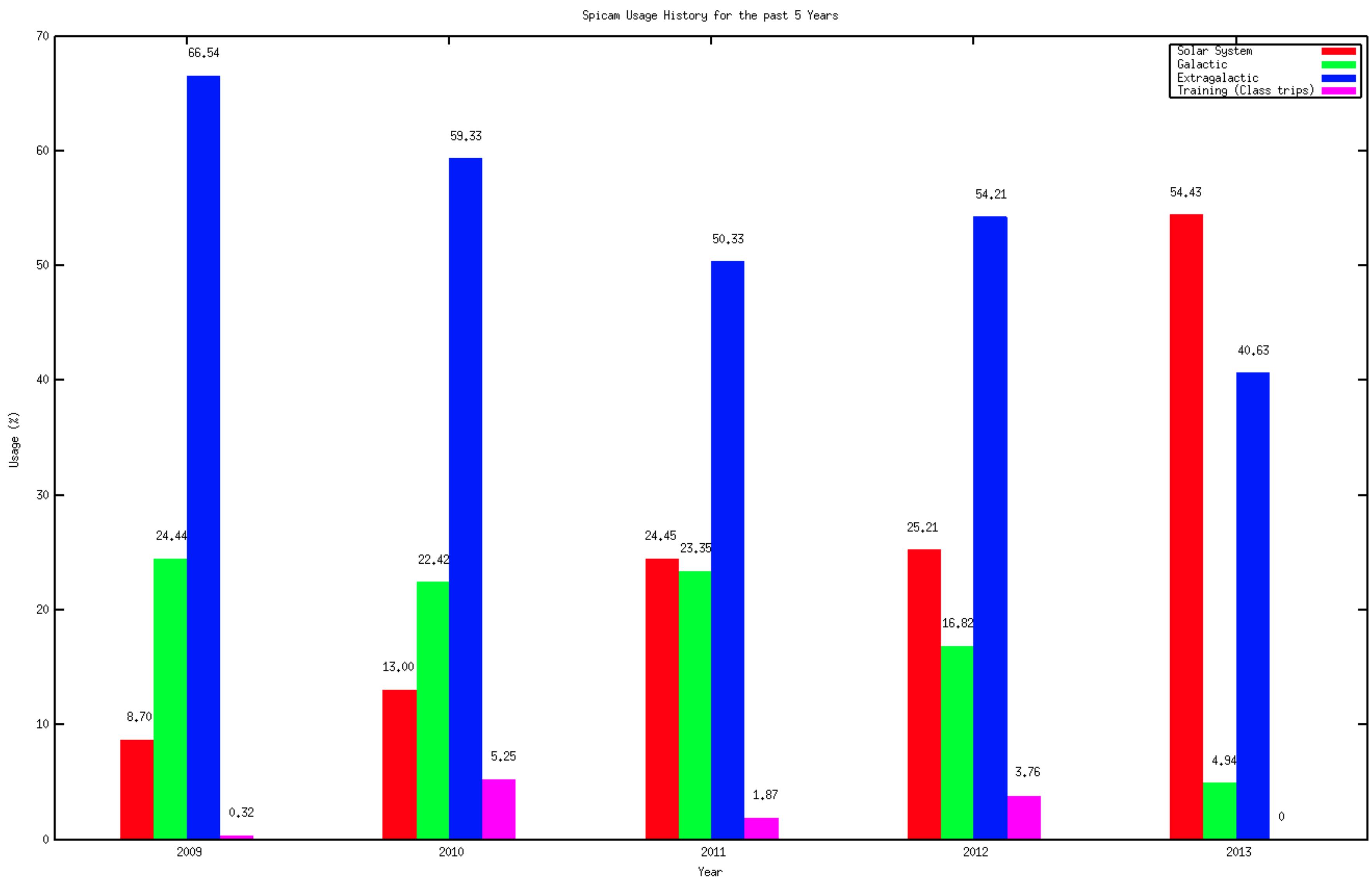
Scheduled Usage (Hours)	2013 (300)	2012 (274)	2011 (431)	2010 (404)	2009 (285)
Percentage [Competing Instruments]	8.5% [D/E/N/P/T] V(~6%)=G,A	8.0% [D/E/N/P/T] V(6%)=G,A,NIIS	11.7% [D/E/N/P/T] V(6.3%)=G,A	10.9% [D/E/N/P/T] V(4.8%)=G,A	8.7% [D/E/N/P/T] V(5.7%)=G,A,NAIC

Scheduled Usage (Hours)	2008 (511)	2007 (555)	2006 (542)	2005 (441)	2004 (378)
Percentage [Competing Instruments]	13.7% [D/E/N/P/T] V(5.1%)=G,A	15.4% [D/E/N] V(10.2%)=C,G,A,P ,NAIC	15.1% [D/E/N] V(10.6%)=C,G,A	12.7% [D/GRIM/E/N] V(5%)=C,G,A,NAIC	13.1% [D/GRIM/E/N] V(5%)=C,G

Scheduled Usage (Hours)	2003 (729)	2002 (576)	2001 (401)	2000 (195*) (*=half nights)	1999 (353)
Percentage [Competing Instruments]	25% [D/GRIM/E] V(7%)=G,AOTF	20% [D/GRIM/E] V(9%)=G,AOTF,L	14% [D/GRIM/E] V(8%)=G,AOTF,L	28.8% [D/GRIM/E] V(11%)=G,AOTF,L,I	17.7% [D/GRIM/E] V=AOTF

Instrument codes: DIS[D], Echelle[E], GRIM2[GRIM], NicFPS[N], Agile[P], Triplespec[T], Visiting(V), GIFS/GFP(G), APOLLO(A), CorMASS (C), NAIC, NIIS, InSb(I), LL FTS (L)
Note: Facility instruments in [ ]

Statistics from Annual Reports to ARC Board of Governors 1999-2012


Spicam Usage History for the past 5 Years
Solar System
Galactic
Extragalactic
Training (Class trips)
Usage (%)
Year
0
10
20
30
40
50
60
70
2009
2010
2011
2012
2013
8.70
24.44
66.54
0.32
13.00
22.42
59.33
5.25
24.45
23.35
50.33
1.87
25.21
16.82
54.21
3.76
54.43
4.94
40.63
0

Solar System Science with SPIcam

(compiled from Q42008 - Q42013 science schedule and proposals)

- Outer solar system bodies (TNOs) (18 proposals in 14 quarters = 138.3 hours)
- Shapes and sizes of Cometary Nuclei (15 quarters = 103.7 hours)
- Pan-STARRS follow-up of comets (7 quarters = 65.7 hours)
- Asteroid classifications (4 quarters = 52 hours)
- Binary asteroids (3 quarters = 30.96 hours)
- Comet compositions and activities (3 quarters = 20 hours)
- Near earth asteroid astrometry (1 quarter = 13 hours)

Galactic Science with SPIcam

(compiled from Q42008 - Q42013 science schedule and proposals)

- Exoplanetary transits (9 proposals in 5 quarters = 100.4 hours)
- Eclipsing binaries in stripe 82 of SDSS survey (7 quarters = 83.9 hours)
- Globular cluster photometry to calibrate Strömgren filter set (8 quarters = 56.1 hours)
- Low mass eclipsing binary photometry (1 quarter = 13.4 hours)
- Halpha/Hbeta study of planetary nebula (1 quarter = 11.9 hours)
- Red Square Nebula (2 quarters = 7.1 hours)
- Star formation in our galaxy (1 quarter = 6.6 hours)
- Pulsar companions (2 quarters = 5.6 hours)

Extragalactic Science with SPIcam

(compiled from Q42008 - Q42013 science schedule and proposals)

- SDSS follow-up star formation in dwarf sphericals + irregulars (15 quarters = 268.9 hours)
- Photometric redshift survey of galaxies in line of sight of QSOs (10 quarters = 181.9 hours)
- Atacama Cosmology Telescope optical follow-up (various) (4 quarters = 83.5 hours)
- Gravitational Lenses (8 quarters = 69.9 hours)
- Pan-STARRS follow-up of supernovas (7 quarters = 65.7 hours)
- Properties of Galaxies (7 quarters = 57.2 hours)
- Galaxy evolutions in compact groups (3 quarters = 52 hours)
- Dwarf Galaxy studies and mergers (5 quarters = 32 hours)
- Dwarf irregular metalicity mapping with Strömgren filters (2 quarters = 31.5 hours)
- Star formation in cores of galaxy clusters (5 quarters = 27.3 hours)
- Star formation in galaxies (3 quarters = 22.75 hours)
- Follow-up transits from SDSS SN survey looking for GRB afterglows (1 quarter = 13.3 hours)

Extragalactic Science with SPIcam

(continued)

(compiled from Q42008 - Q42013 science schedule and proposals)

- Arecibo optical follow-up (2 quarters = 12.6 hours)
- Nearby low surface brightness galaxies near QSO sight lines (1 quarter = 10.8 hours)
- Tidal Formations in galaxies (2 quarters = 10.6 hours)
- SDSS Stripe 82 supernova follow-up (2quarters = 10 hours)
- Black Holes (2 quarters = 9 hours)
- Mapping the circum-galactic medium with QSOs (1 quarter = 6.6 hours)
- Diffuse stellar light at center of massive clusters (1 quarter = 6.5 hours)
- Star Bursting Blue Compact Galaxies in Intermediate Redshift Clusters (1 quarter = 6.4 hours)
- Wolf-Rayet Galaxies (1 quarter = 5.5 hours)
- Intercluster medium (1 quarter = 5.1 hours)
- Metalicities of galaxies with historical SN (1 quarter = 4.7 hours)
- Quasar discovery (1 quarter = 2.9 hours)

Publications based on SPIcam Data

(Papers and Theses, 11/2010-11/2012)

Churchill, C. W., Kacprzak, G. G., Steidel, C. C., Spitler, L. R., Holtzman, J. A., Nielsen, N. M., & Trujillo-Gomez, S. 2012, "Quenched Cold Accretion of a Large Sacle Metal Poor Filament due to Virial Shocking in the Halo of a Massive z=0.7 Galaxy", ApJ, accepted, arXiv:1205.0595

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Davenport, J.R.A., Becker, A., West, A.A., Bochanski, J.J., Hawley, S.H., Holtzman, J., Gunning, H.C., Hilton, E.J., Munshi, F.D., Albright, M., 2012, "The Very Short Period M Dwarf Binary SDSS J001641-000925", submitted to ApJ

Grundy, W.M., et al., 2012, "Mutual Events in the Cold Classical Transneptunian Binary System Sila and Nunam", Icarus, 220, 74

Hart, Q.N., Stocke, J.T., et al., 2011 "The evolution of radio galaxies and X-ray point sources in Coma Cluster progenitors since z~1.2", ApJ 740, 59

Hughes, J., Wallerstein, G., 2011, "Determining the photometric metallicities of dSph stellar populations", arXiv:1108.5020

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Kacprzak, G. G., Churchill, C. W., Steidel, C. C., Spitler, L. R., & Holtzman, J. A. 2012, "Discovery of Multi-Phase Cold Accretion in a Massive Galaxy at z=0.7", MNRAS, accepted, arXiv:1208.4098

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Blackburne, J.A., Kochanek, C.S., 2010, "The Effect of a Time Varying Accretion Disk Size on Quasar Microlensing Light Curves", submitted to ApJ., astro-ph/1002.3126

Diehl, H.T., Allam, S.S., Annis, J., Buckley-Geer, E.J., Frieman, J.A., Kubik, D., Kubo, J.M., Lin, H., Tucker, D., West, A., 2009, "The Sloan Bright Arc Survey: Four Strongly Lensed Galaxies with Redshift > 2", ApJ, 707, 686.

Dilday, B., etal., 2010, "Measurements of the Rate of Type Ia Supernovae at Redshift <~ 0.3 from the Sloan Digital Sky Survey II Supernoae Survey", ApJ, 713, 1026

Hart, Q., 2009, "AGN in Clusters of Galaxies", Ph.D. thesis, Univ of Colorado, Dec 2009

Hart, Q.N., Stocke, J.T., Hallman, E.J., 2009, "X-ray Point Sources and Radio Galaxies in Clusters of Galaxies", ApJ, 705, 854

Keeney, B.A., Stocke, J.T., Danforth, C.W., Carilli, C., 2010, "The Quasar/Galaxy Pair PKS 1327-206/ESO 1327-2041: Absorption Associated with a Recent Galaxy Merger", submitted to AJ, astro-ph/1009.5993

McGreer, I.D., etal., 2010, "SDSS J094604.90+183541.8: A Gravitationally Lensed Quasar at z= 4.8", AJ, 140, 370

Rest, A., etal.., 2010, "Direct Confirmation of the Asymmetry of the Cas A SN Explosion with Light Echoes", submitted to ApJ, astro-ph/1003.5660

Publications based on SPIcam Data

(Papers and Theses, 11/2008-11/2009)

Coughlin, J.L., Stringfellow, G.S., Becker, A.C., Lopez-Morales, M., Mezzalira, F., Krajci, T., 2008, "New Observations and a Possible Detection of Parameter Variations in the Transits of Gliese 436b", ApJ 689, L149

Holtzman, J., et al., 2008, "The Sloan Digital Sky Survey-II: Photometry and Supernova Ia Light Curves from the 2005 Data", AJ, 136, 2306

Holtzman, J., Eisenstein, D., Strauss, M., York, D., Anderson, K., Walterbos, R., Klaene, M., Gillespie, B., Anderson, S., Turner, E., 2009, "Apache Point Observatory: Facilities, Operations, and Partnerships", Astro2010: The Astronomy and Astrophysics Decadal Survey, Position Papers, no 23

Hughes, J., Wallerstein, G., Bossi, A., 2008, "The Age and Metallicity of the Bootes I System", AJ 136, 2321, astro-ph/0810.4353

Inada, N., Oguri, M., Shin, M.-S., Kayo, I., Strauss, M.A., Morokuma, T., Schneider, D.P., Becker, R.H., Bahcall, N.A., York, D.G., 2008, "Five New High-Redshift Quasar Lenses from the Sloan Ditial Sky Survey", AJ, 137, 4118, astro-ph/0809.0912

Kubo, J.M., Allam, S.S., Annis, J., Buckley-Geer, E.J., Diehl, H.T., Kubik, D., Lin, H., Tucker, D., 2009, "The Sloan Bright Arc Survey: Six Strongly Lensed Galaxies at z = 0.4 - 1.4", ApJ, 696, L61

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Miller, C., Chanover, N.C., 2009, "Resolving Dynamic Parameters of the August 2007 Titania and Ariel Occultations by Umbriel", Icarus, 200, 343

Stringfellow, G.S., Coughlin, J.L., Lopez-Morales, M., Becker, A.C., Krajci, T., Mezzalira, F., Agol, E., 2009, "Transit Timing Observations of the Extrasolar Hot-Neptune Planet GL436b", in Cool Stars, Stellar Systems, and the Sun, AIP Conf. Proc. 1094, 481

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(Papers and Theses, 11/2007-11/2008)

Anguita, T., Schmidt, R.W., Turner, E.L., Wambsganss, J., Webster, R.L., Loomis, K.A., Long, D., McMillan, R., 2008, "The Multiple Quasar Q2237+0305 Under a Microlensing Caustic, A&A 480, 327

Dilday, B., Kessler, J.A., Frieman, J., Holtzman, J., etal., 2008, "A Measurement of the Rate of Type-Ia Supernovae at Redshift z ~ 0.1 from the First Season of the SDSS-II Supernova Survey", ApJ 682, 262

Frieman, J., etal, 2008, "The SDSS-II Supernova Survey: Technical Summary", 2007, AJ. 135, 338 (astro-ph/0708.2749)

Morgan, C.W., Kochanek, C.S., Dai, X., Morgan, N.D., Falco, E.E., 2008, "X-Ray and Optical Microlensing in the Lensed Quasar PG 1115+080", ApJ 689, 755

Nitta, A., Kleinman, S.J., etal, 2008, "New Pulsating DB White Dwarf Stars from the Sloan Digital Sky Survey", ApJ, in press, astro-ph/0809.0921

Oguri, M., Inada, N., Clocchiatti, A., Kayo, I., Shin, M., Hennawi, J., Strauss, M.A., Morokuma, T., and Schneider, D. 2008, "Discovery of Four Gravitationally Lensed Quasars from the Sloan Digital Sky Survey", AJ 135, 520

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SPIcam filter usage

Broad Bandpass Filters	Size (in^2)	2013	2012	2011	2010	2009
MSSSO U	3x3	2.85	1.25	0.17	0.12	0
MSSSO B	3x3	0	0.3	0.07	0.04	0.25
MSSSO V	3x3	6.42	0.87	5.97	0.03	6.41
MSSSO R	3x3	22.81	35.3	22.49	9.87	10.69
MSSSO I	3x3	9.28	5.96	4.68	3.39	1.2
SDSS u	3x3	1.71	3	5.43	10.71	2.14
SDSS g	3x3	2.32	5.98	7.37	10.25	7.34
SDSS r	3x3	25.45	10.59	12.18	19.63	6.21
SDSS i	3x3	10.52	14.14	5.41	9.01	8.99
SDSS z	3x3	4.27	5.3	6.25	9.9	8.03
Harris R (6472/1458)	3x3	0	0	0	0.91	0
BG40 (4750/3100)	3x3	0	0.82	0	0	0
Strömgren y (5450/150)	3x3	0.92	2.09	3.45	0.5	6.83
Strömgren v (4100/200)	3x3	0	1.31	3.21	0.89	13.18
Strömgren u (3500/300)	3x3	0	0	0.75	1.72	0.04
Strömgren b (4700/200)	3x3	1.32	3.51	3.6	0.55	8.49
Washington C (4000/1000)	3x3	3.69	9.59	10.58	4.86	1.2
Washington M (5000/1200)	2x2	0	0	0	1.66	0
Washington T2	2x2	0	0	0	2.61	0
Comet Filters C2	2x2	0.3	0	0.26	0	0
Comet Filters CN	2x2	0.55	0	0	0	0
Comet Filters BC4	2x2	0.4	0	0.52	0	0
Hale Bopp RC3	2x2	0.37	0	0	0	0
Gunn-g	2x2	0	0	0	0	1.35
OPEN/CLEAR	3x3	0	0	0.01	0.24	0
Subtotal (%)		**93.18**	**100.01**	**92.4**	**86.89**	**82.35**

Compiled from instrument logs (Oct 1 - Sep 30)
*Flats excluded

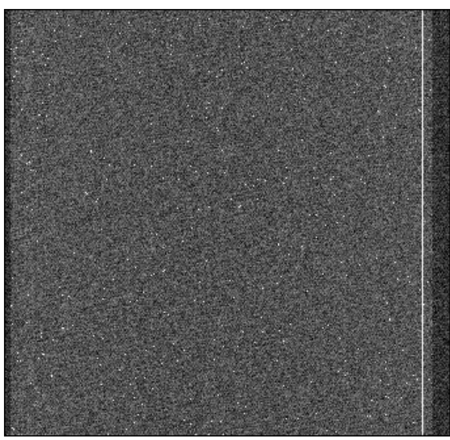
SPIcam filter usage

Narrow Bandpass Filters	Size (in^2)	2013	2012	2011	2010	2009
CU SII (6725/90)	3x3	0	0	0.18	1.91	0.64
CU Ha (6563/90)	3x3	0	0	0.18	0.8	0.62
APO Ha (6563/100)	2x2	0.03	0	3.34	0	0
Hodge Ha (6563/25)	2x2	0	0	0.52	0	0.18
Hodge 6629/25	2x2	0	0	0.24	0	0.23
Hodge 6607/20	2x2	0	0	0.54	0	0
Hodge 6585/20	2x2	0	0	0	0	0
Hodge Hb (4860/25)	2x2	0	0	0	0	3.85
NMSU 6776/75	2x2	0	0	0.25	1.74	2.46
NMSU 6736/80	2x2	0	0	0.25	0.26	0.79
NMSU 6676/75	2x2	0	0	0	0	0
NMSU 6650/80	2x2	2.63	0	0.67	2.01	2.14
NMSU 6610/75	2x2	0.93	0	0.52	0.34	1.19
NMSU 6580/25	2x2	0	0	0.2	0	0
NMSU 6570/75	2x2	1.17	0	0	1.3	1.37
NMSU 6550/80	2x2	0	0	0	0	0.16
NMSU 6450/100	2x2	2.06	0	0.26	1.34	1.69
NMSU 5007/60	2x2	0	0	0	0	2.35
DDO-51 5130/154	2x2	0	0	0	3.4	0
UW-WSU 4686/60	2x2	0	0	0.47	0	0
Subtotal (%)		**6.82**	**0**	**7.62**	**13.1**	**17.67**
Total (%) (broadband + narrowband)		**100**	**100.01**	**100.02**	**99.99**	**100.02**

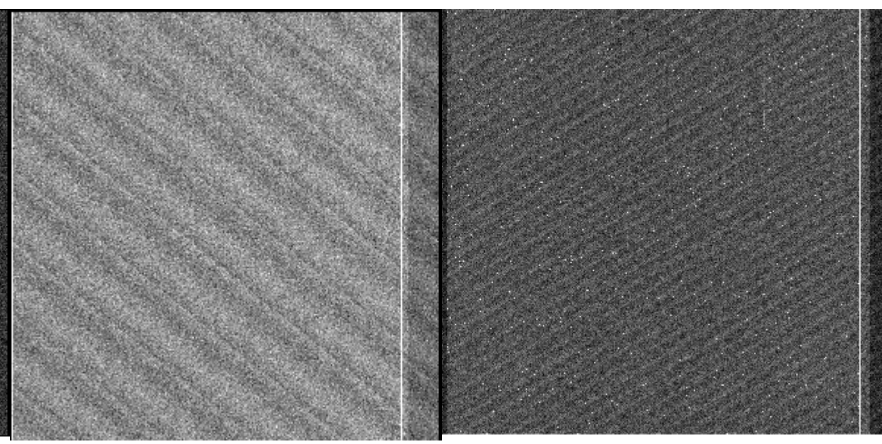
Compiled from instrument logs (Oct 1 - Sep 30)
*Flats excluded

SPIcam Retirement

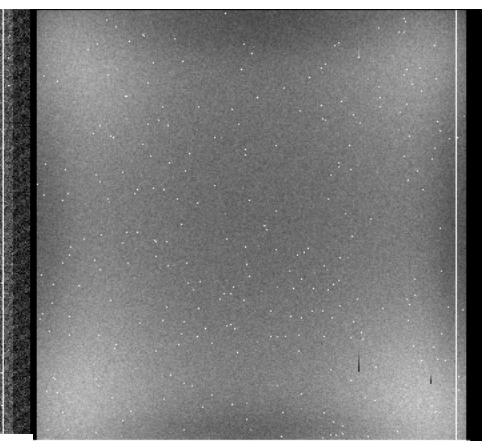
- Lack of documentation
- Minimal serviceability of electronics
- Noise issues (pattern and ion pump induced dark current, see below)
- Long readout times between exposures (120s Full frame, unbinned or 42s Full frame, binned 2x2)
- Starting to see more bad columns / charge traps appear



Normal 900s dark



Pickup noise examples (darks and biases)



ion pump induced noise

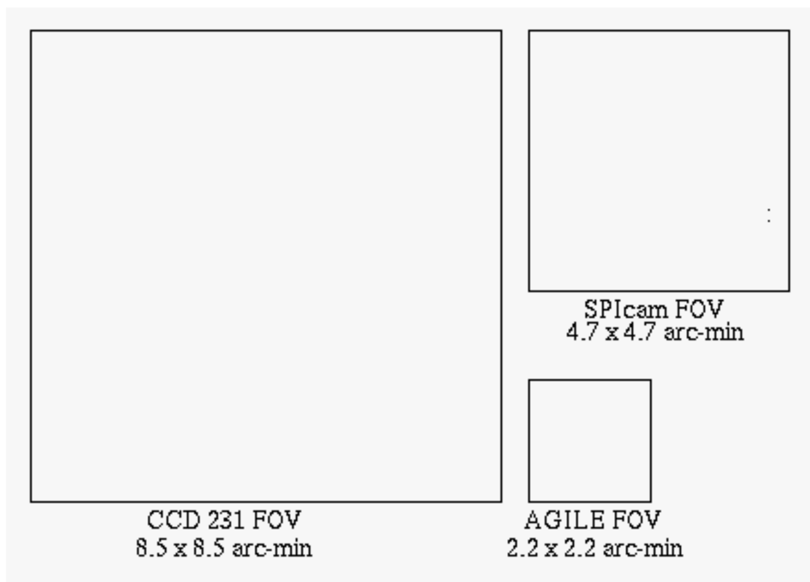
Design Requirements Review

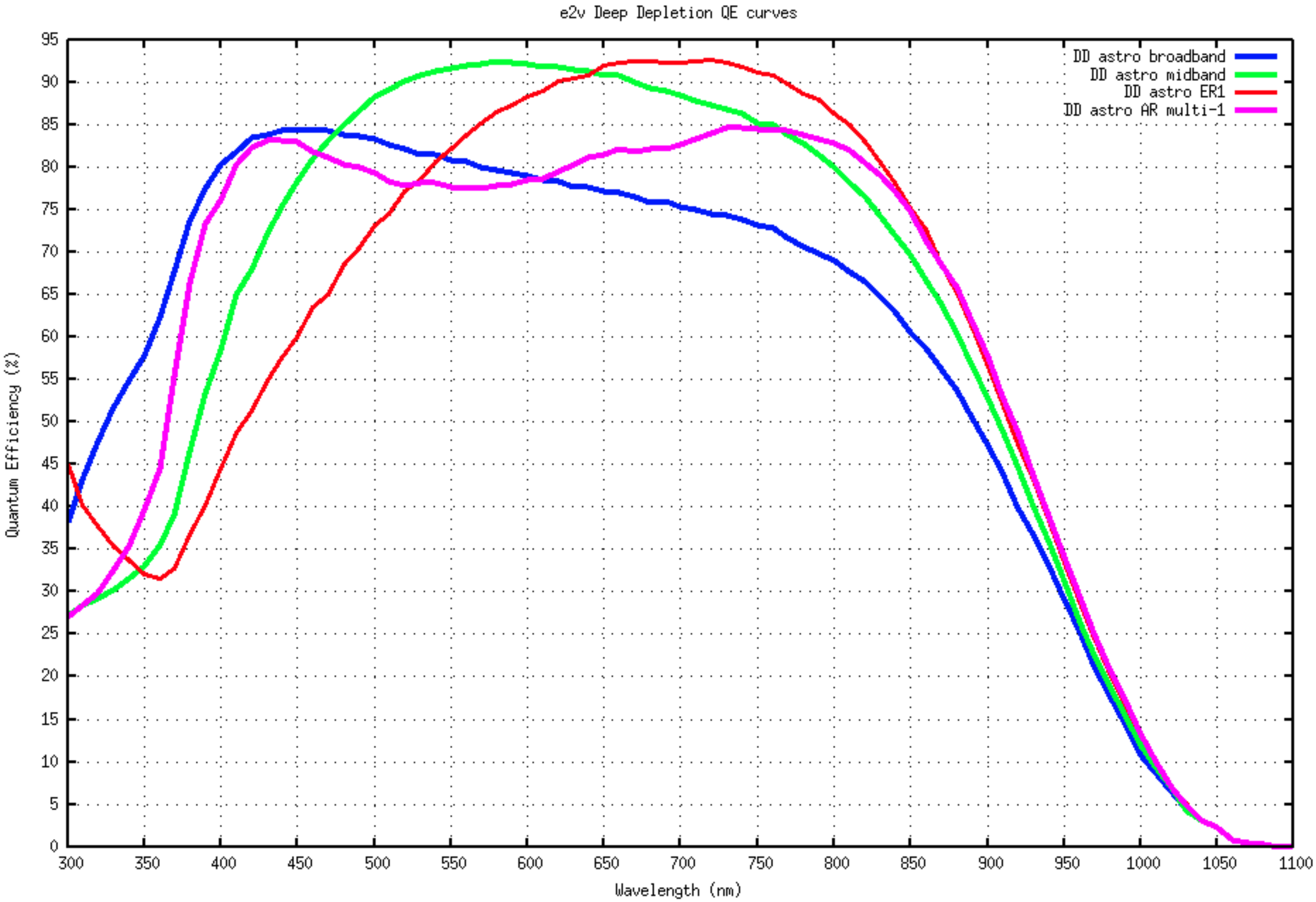
In March 2013, a proposal for an imager on the APO 3.5m telescope was presented to the users committee. This proposal outlined several options for a general-purpose optical imager to replace the aging and hard to maintain SPICam. Feedback and discussion over the last couple months has allowed us to make some design decisions. From this feedback it was determined that the most important properties of this imager should include **good throughput, good spatial resolution, fast readout, and capability to use narrow band filters (both existing and new).** Many institutions felt that the proposed widest field option (~12'x12' FOV) would not present a significant scientific advantage compared to the increased cost of the detector. Other design requirements included:

- ~ 9'x9' FOV using focal reduction (same 4.7'x4.7' FOV using 3x3 inch and 3'x3' FOV using 2x2 inch filters that SPIcam currently gives)
- NA2 mounted compact instrument (at first), must meet all the 20 question requirements document of a visiting or facility instrument
- Leach electronics
- Cryotiger cooling
- Photometric precision shutter
- Low read noise and negligible dark current
- RMS spot sizes less then typical seeing disk of 1 arc-second but goal of 0.75 arc-second seeing

	Imager[2]	**SPIcam**	**AGILE**
CCD	e2v CCD 231 w/ fringe suppression	SITe/TK2048E	e2v CCD 47-20 Frame Transfer Device
Chip coating[1]	DD Astro Broadband	VIS AR	Broadband AR
Format	4096(H) x 4112(V)	2048 x 2048	1024 x 1024 (Active and Storage)
Pixel Size	15μm x 15μm	24μm x 24μm	13μm x 13μm
Imaging Area	61.4mm x 61.4mm	49mm x 49mm	13.3mm x 13.3mm
Dark Current (@ ~ 170K)	3e^-/pixel/hour	3.6 e^-/pixel/hour	13.3 e^-/pixel/second
Readnoise	5 e^-/sec @ 1MHz	5.7 e^-/sec	6.62 e^-/sec @ 1MHz
	2 e^-/sec @ 50KHz		3.66 e^-/sec @ 100kHz
Gain	2.6 e^-/DN	3.36 e^-/DN	Selectable: (0.9 - 4) e^-/DN
Full Well Depth	350Ke^-	150Ke^-	100Ke^-
Read out time	4.2 seconds @ 1MHz full frame no binning	120 seconds full frame binned 1x1	0.46 seconds @ 1MHz full frame binned 2x2
	84 seconds @ 50kHz full frame no binning	42.3 seconds full frame binned 2x2	3.1 seconds @ 100kHz full frame binned 2x2
Peak QE (@350nm)[1]	55%	48%	38%
Peak QE (@400nm)[1]	81%	84%	64%
Peak QE (@600nm)[1]	80%	88%	98%
Peak QE (@800nm)[1]	69%	76%	80%
f/ratio	8	10.3 (native telescope)	~6.1
Field of View	7.6 arcmin x 7.6 arcmin	4.7 arcmin x 4.7 arcmin	2.2 arcmin x 2.2 arcmin
Pixel Scale	0.111"/pixel	0.141"/pixel (typically binned 2x2)	0.129"/pixel (typically binned 2x2)
Operating Temperature (K)	160K	160K	233K (-40C)
Limiting Magnitude	? (Background Limited)	? (Background Limited)	? (Readnoise Limited)
(Mag for griz w/ 300s results in S/N = 10)			
Fringing[3]		None	None

Note (1) See QE Curves (next page)
Note (2) To be named
Note (3) See fringing plot




e2v Deep Depletion QE curves
DD astro broadband
DD astro midband
DD astro ER1
DD astro AR multi-1
Quantum Efficiency (%)
Wavelength (nm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
300
350
400
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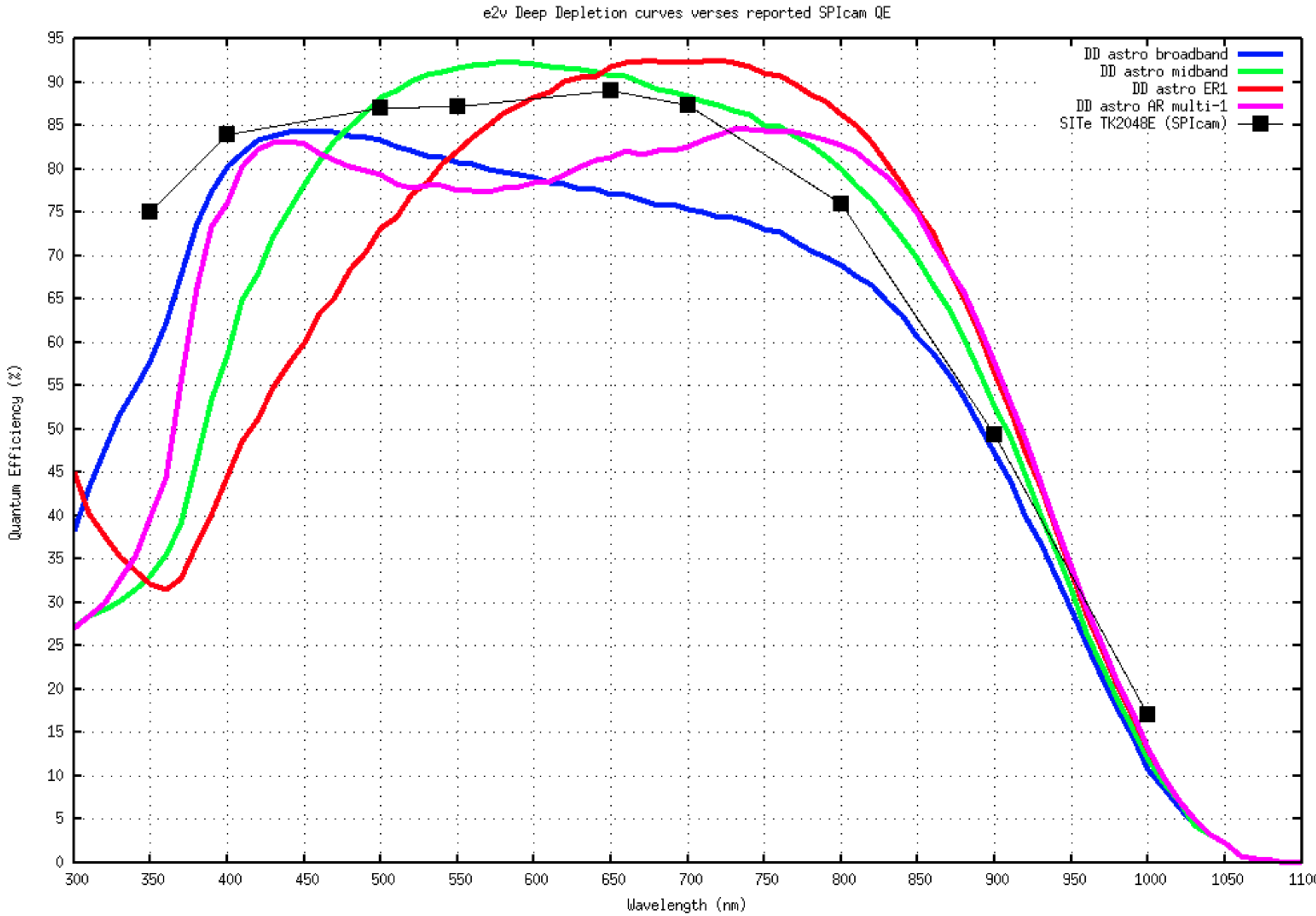
900
950
1000
1050
1100



e2v Deep Depletion curves verses reported SPIcam QE
DD astro broadband
DD astro midband
DD astro ER1
DD astro AR multi-1
SITe TK2048E (SPIcam)
Quantum Efficiency (%)
Wavelength (nm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
300
350
400
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500
550
600
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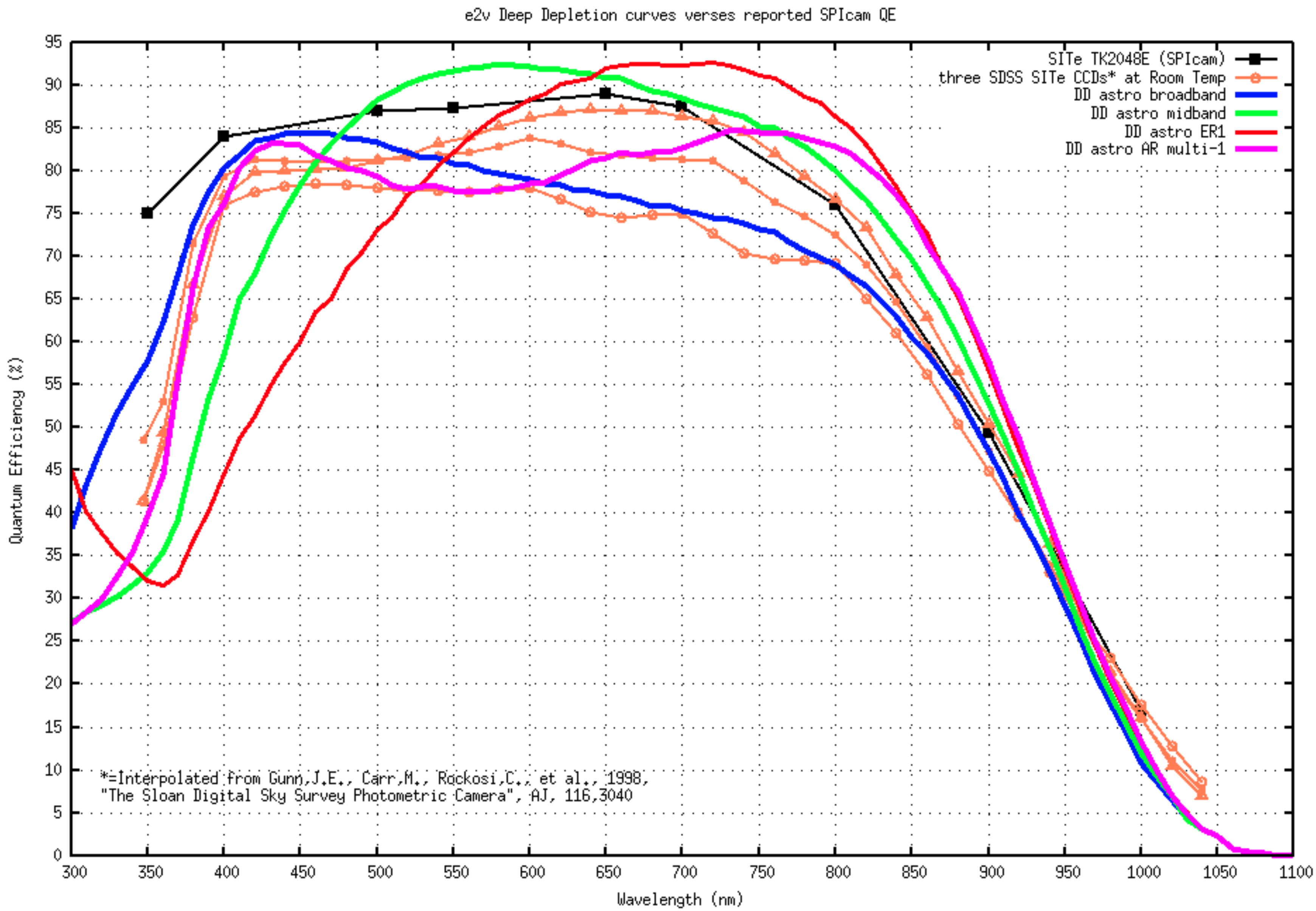
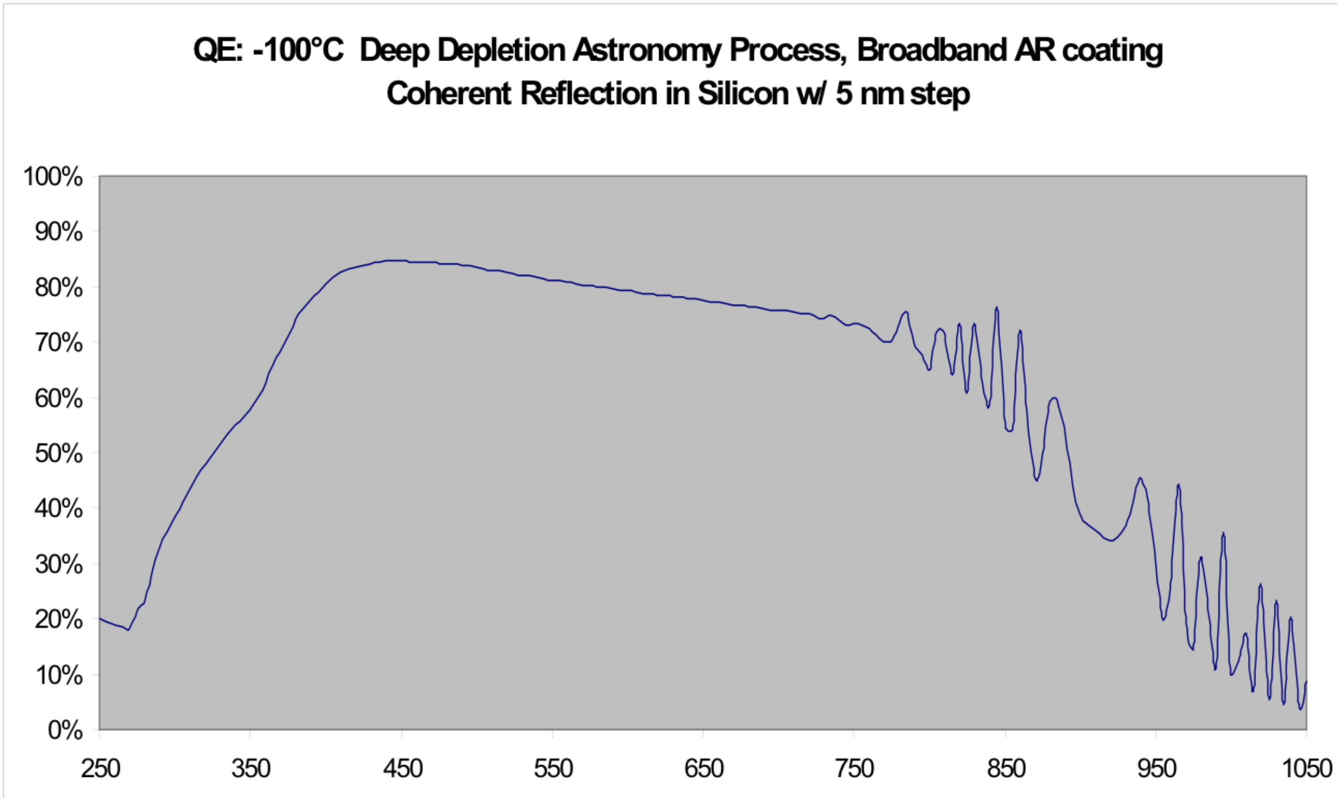
700
750
800
850
900
950
1000
1050
1100


e2v Deep Depletion curves verses reported SPIcam QE
SITe TK2048E (SPIcam)
three SDSS SITe CCDs* at Room Temp
DD astro broadband
DD astro midband
DD astro ER1
DD astro AR multi-1
*=Interpolated from Gunn,J.E., Carr,M., Rockosi,C., et al., 1998,
"The Sloan Digital Sky Survey Photometric Camera", AJ, 116,3040
Quantum Efficiency (%)
Wavelength (nm)

Etaloning in deep depletion astro broadband device



This figure shows fringe response for an AR coated back illuminated deep depletion device. With the addition of fringe suppression and an AR coating the fringe amplitude would decrease to 1-2% per discussions with e2v.

Anticipated Performance Improvements with new Imager

- More accurate shutter for shorter exposure times (10ms accuracy expected for as short as 0.5sec exposures)
- Shorter overall exposure times by approximately a factor of 2.5
  - Focal Reduction from f/10.3 to f/8 (m = 0.95) increases the image surface brightness per pixel and shortens exposures by factor of $(1/m)^2 = 1.1$
  - Standard binning of 3x3 will reduce the exposure time by a factor of 2.25 times (9/4 = 2.25) compared to the same exposure using SPIcam with 2x2 binning.

Increased Science Potential with new Imager

- Larger FOV for select solar system science
- Larger FOV for comparison stars when doing differential photometry
- Larger FOV for imaging of globular or open clusters
- Larger FOV for imaging nebulas and galaxy clusters
- Larger FOV time series photometry (than AGILE in slow readout rate) given faster chip readout (full frame and sub-regions)
- Potential of much larger narrow band imaging projects (requiring purchase of larger filters dependant on science goals)
- Measurable sky or more foreground stars available in the image when studying nearby galaxies
- Other? Depends on the imagination and science interests of our various users