JOHNS HOPKINS UNIVERSITY Applied Physics Laboratory
Laurel MD 20723-6099

SRP Number
ICY0243X, Phase E Number
December XX, 2002

To: Distribution

From: N. R. Izenberg

Subject: IFOV, Ensquared Energy, and Point Spread Functions for CONTOUR imagers

References: (1) N. R. Izenberg, Master Calibration Record Parts 1-4

(2) M. R. Keller, B. Gotwols, Imagers Report SRO-02M-30

Summary

Instantaneous field of view (IFOV), ensquared energy (EE), and point spread functions (PSF) are determined for Comet Nucleus Tour (CONTOUR) imagers: CONOUR Remote Imager/Spectrometer (CRISP) and CONTOUR Forward Imager (CFI). Parameters were determined from calibration observations of point sources in the APL optical calibration facility (OCF) assisted by multiple repositioning of the imagers on a motion stage, and multiple point source images with varied exposure times and neutral density filters. IFOV, EE, and PSF were all acceptable for flight.

Introduction

CONTOUR's CFI and CRISP Imager are the two CCD-camera instruments on the CONTOUR spacecraft. Each imager has a 10-filter filter wheel in between the telescope optics and the CCD. Nine of the filters are "spectral" and one is a "clear" or wide-bandpass filter. Accurate knowledge of the bandpasses of the imager filters is required for analysis of the flight data.

IFOV: Characterize IFOV using point source scanned across the FOV to known angles using the motion stage

EE: Characterize EE of point source centered in CCD with optimal exposure times.

PSF: Characterize inner to medial PSF using centered point sources and neutral density filters.

To support these analyses, a series of point source images were collected images were collected during the calibration of the instruments. Broad-spectrum light was generated in the APL Optical Calibration Facility (OCF) using the facility monochromator, exit pinholes, and inserted neutral density filters. A high-resolution calibration of the test equipment was completed in summer '01 and supplemented during CONTOUR calibration.

Test Conditions

The test setup for IFOV, EE, and PSF determinations utilized the OCF monochromator fed by a small, extended light source. The monochromator narrowed the incoming broadband light to the instrument to a near-pinpoint, unrestricted in wavelength (0^{th} order light). For each imager filter a series of dark images was taken followed by a series of point-source images. The nominal image series included dark observations before and after the point-source images, and a 5x5 milli-degree "box" scan of the stage upon which each instrument was mounted. The scan resulted in 25 images with .001 degree of stage movement in rotation and/or azimuth between frames. The step size was sub-pixel for both instruments. Nominally, box scans were conducted in each of the 4 corners of the imager CCD and in the center. Where possible, point source observation/scans were performed for each filter of each imager. Some observations were repeated with varying exposure times (including oversaturated images), and/or with neutral density filters in place.

Images were analyzed after subtracting background, dark current, and frame transfer smear (Ref. 2). Additional dark correction was provided by averaging pixels to either side of the point source in illuminated images.

The data for imager IFOV, EE, and PSF were taken during pre-calibration and calibration runs CIBMA_PIF for CRISP and CF0AA_PFO, CF0CC_PFO, CFCCC_PIF for CFI. These calibration observations are documented in the Master Calibration Record (MCR, Ref. 1).

Results

IFOV:

We characterized imager IFOV using point source scanned across the FOV to known angles using the motion stage. Data sets utilized were pre-calibration data for CFI's clear filter and post-environmental test calibrations for CRISP filters 1 and 6-10. The 5x5 milli-degree stage scan "box" ensured that the point source would be well centered (and bright) in at least one imager pixel. We determined the brightest pixel, from sub-pixel dithering along the grid of points, at the center and each corner of the imager FOV. The average distances between pairs of brightest pixels in each dither determined (at each wavelength where possible), determined the IFOV.

CFI: IFOV = 43.40±0.06 μrad, FOV = 2.547±0.003° (Figure 1, Table 1)
CRISP: IFOV = 20.23±0.01 μrad, FOV = 1.187±0.005° (Figure 2, Table 2)

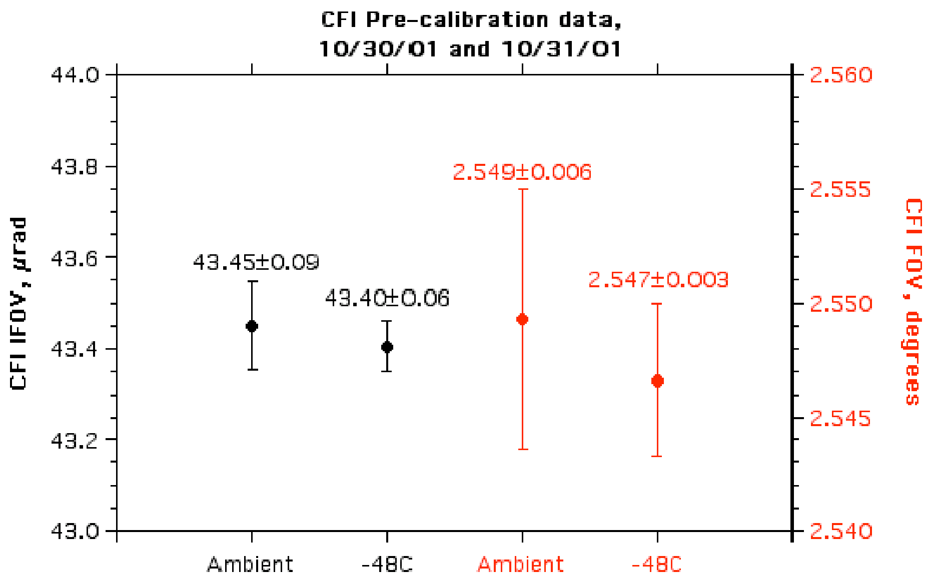

Fig. 1. CFI IFOV and FOV from pre-calibration data.

Table 1. Data for CFI IFOV and FOV.

Ambient (Room) Temperature

Position	Filename	1x1frac fraction max signal	5x5ctrX pixel	5x5ctrY pixel	Angle X/˚ motion stage	Angle Y/˚ motion stage
Center	CF0AA_PFO_52.fit	0.20620889	500.82975	557.79507	-57.973	3.103
Upper left corner	CF0AA_PFO_99.fit	0.21400444	914.86594	170.17417	-56.970	2.100
Upper right corner	CF0AA_PFO_129.fit	0.20212415	112.07851	142.94995	-58.971	2.104
Lower right corner	CF0AA_PFO_169.fit	0.15193505	83.990784	946.23219	-58.973	4.102
Lower left corner	CF0AA_PFO_192.fit	0.18073554	887.03337	973.83354	-56.973	4.104

	delta pixels (delp)	delta radians (delr)	IFOV in urad delr/(delp*10^6)	focal length in mm 0.013/(IFOV*10^6)
c-ul	567.1648162	0.02475671	43.64993988	297.824007
ul-ur	803.2489128	0.034924079	43.47852584	298.9981778
lr-ur	803.7731505	0.034871666	43.38496061	299.6430057
ll-lr	803.5167885	0.034906573	43.44224478	299.247888
c-ur	568.5279238	0.024645641	43.34992215	299.8851983
ul-lr	1136.934288	0.049427032	43.47395711	299.0295999
ul-ll	804.1411785	0.034976408	43.49535728	298.8824742
ur-ll	1136.187738	0.049340648	43.42649208	299.3564383
c-lr	569.7702342	0.024670324	43.29872362	300.2397972
c-ll	567.6629675	0.024695007	43.50293743	298.8303955

	IFOV in urad	focal length in mm	width of FOV, deg.
mean	**43.45030608**	**299.1936982**	**2.54926977**
st dev	**0.096589248**	**0.664484207**	**0.005666981**

Cold Temperature

Position in CCD	Filename	1x1frac fraction max signal	5x5ctrX pixel	5x5ctrY pixel	Angle X/˚ motion stage	Angle Y/˚ motion stage
Center	CF0AC_PFO_22.fit	0.23009875	499.93399	556.95246	-57.973	3.102
Upper left corner	CF0AC_PFO_48.fit	0.24574293	915.81102	170.19983	-56.972	2.103
Upper right corner	CF0AC_PFO_74.fit	0.23244919	112.98428	142.10149	-58.972	2.104
Lower right corner	CF1AC_PFO_34.fit	0.20741394	83.840254	945.02314	-58.971	4.101
Lower left corner	CF0AC_PFO_94.fit	0.18183556	888.09664	973.0436	-56.974	4.104

	delta pixels (delp)	delta radians (delr)	IFOV in urad delr/(delp*10^6)	focal length in mm 0.013/(IFOV*10^6)
c-ul	567.9183928	0.024682674	43.46165716	299.1142273
ul-ur	803.3183	0.03490656	43.45296244	299.1740786
lr-ur	803.4504031	0.0348542	43.38064921	299.6727859
ll-lr	804.7443573	0.034854235	43.31094059	300.1551068
c-ur	567.3018644	0.024645641	43.44361051	299.2384806
ul-lr	1136.893362	0.049328302	43.3886796	299.6173223
ul-ll	803.3219815	0.034924026	43.47450597	299.0258247
ur-ll	1136.337961	0.049340648	43.42075113	299.3960183
c-lr	568.9752629	0.024645641	43.31583962	300.1211592
c-ll	569.036097	0.024695031	43.39800473	299.5529422

	IFOV in urad	focal length in mm	width of FOV, deg.
mean	**43.4047601**	**299.5067946**	**2.546597545**
st dev	**0.057527577**	**0.397220418**	**0.003375196**

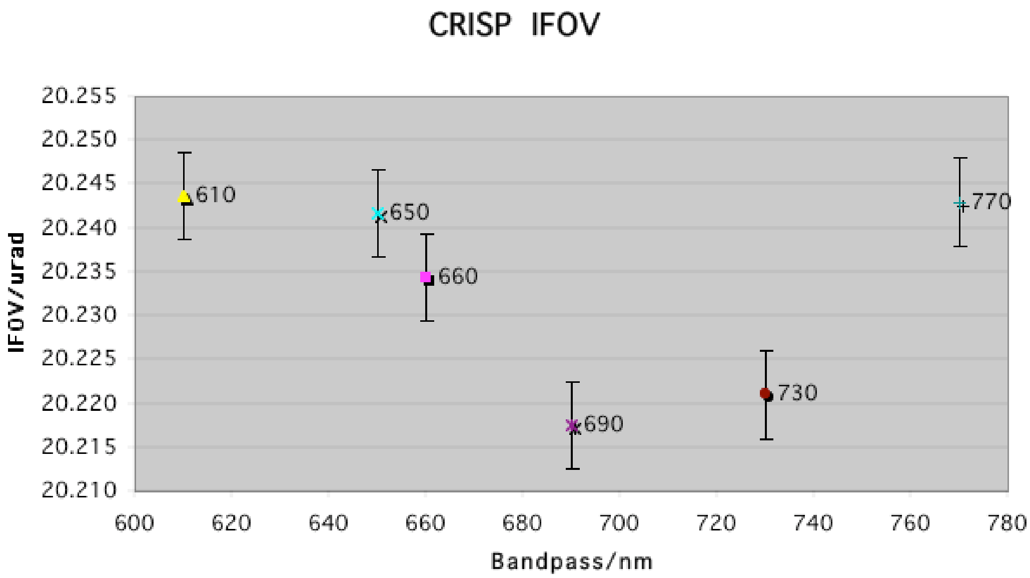

Fig. 2. CRISP IFOV for multiple imager filters.

Table 2. Data for CRISP IFOV and FOV.

FILTER 1

Position	Filename	1x1frac	5x5ctrX	5x5ctrY	AX1/°	AX2/°	Position
Center	357_CIBMA_PIF_01_0031.fit	0.336	490.98864	535.92115	-1.042	1.122	Center
Upper right	357_CIBMA_PIF_01_0283.fit	0.238	934.85305	956.62507	-0.54	0.622	Corner 1
Lower right	357_CIBMA_PIF_02_0061.fit	0.365	910.00349	96.872798	-0.542	1.618	Corner 2
Upper left	357_CIBMA_PIF_02_0311.fit	0.321	71.873001	982.40605	-1.542	0.618	Corner 3
Lower left	357_CIBMA_PIF_02_0566.fit	0.308	49.96306	117.05776	-1.542	1.619	Corner 4

10.11 ms exposure	delta pixels	delta radians	IFOV in urad	focal length in mm
	(delp)	(delr)	delr/(delp*10^6	0.000024/(IFOV*10^6)
c-ul	612.38	0.012391	20.2339	1.18612807
ul-ur	863.37	0.017488	20.2560	1.18483405
lr-ur	860.11	0.017383	20.2108	1.18748652
ll-lr	860.28	0.017453	20.2880	1.18296656
c-ur	611.56	0.012366	20.2204	1.1869181
ul-lr	1219.28	0.024683	20.2437	1.18555296
ul-ll	865.63	0.017471	20.1828	1.18913254
ur-ll	1219.80	0.024670	20.2250	1.18664955
c-lr	606.91	0.012292	20.2536	1.18497452
c-ll	608.24	0.012304	20.2296	1.18637965

	IFOV in urad	focal length in	width of FOV, deg.
			(focal length *1024 pixels*180/pi/10^6)
mean	**20.2344**	**1.18610225**	**1.18716981**
st dev	**0.028524411**	**0.00167186**	**0.00167355**

FILTER 6

Position	Filename	1x1frac	5x5ctrX	5x5ctrY	AX1	AX2	Position
Center	357_CIBMA_PIF_01_0156.fit	0.261	491.14855	536.39497	-1.042	1.12	Center
Upper right	357_CIBMA_PIF_01_0408.fit	0.216	935.06441	957.09483	-0.54	0.622	Corner 1
Lower right	357_CIBMA_PIF_02_0204.fit	0.280	913.01917	94.182447	-0.539	1.621	Corner 2
Upper left	357_CIBMA_PIF_02_0437.fit	0.246	73.155651	980.84852	-1.541	0.618	Corner 3
Lower left	357_CIBMA_PIF_02_0706.fit	0.270	50.008869	115.17527	-1.542	1.622	Corner 4

300 ms exposure	delta pixels	delta radians	IFOV in uradians	focal length in mm
				0.000024/(IFOV*10^6)
c-ul	610.13	0.012354	20.2477	1.1853174
ul-ur	862.24	0.017471	20.2623	1.1844667
lr-ur	863.19	0.017436	20.1992	1.18816544
ll-lr	863.27	0.017506	20.2784	1.18352523
c-ur	611.60	0.012341	20.1791	1.18935198
ul-lr	1221.29	0.024744	20.2609	1.18454986
ul-ll	865.98	0.017523	20.2349	1.18606777
ur-ll	1221.54	0.024707	20.2265	1.1865648
c-lr	611.17	0.012391	20.2738	1.1837923
c-ll	609.94	0.012366	20.2741	1.18377668

	IFOV in urad	focal length in	width of FOV, deg.
			(focal length *1024 pixels*180/pi/10^6)
mean	**20.2437**	**1.18555782**	**1.18771583**
st dev	**0.033705475**	**0.00197638**	**0.00197753**

FILTER 7

Position	Filename	1x1frac	5x5ctrX	5x5ctrY	AX1	AX2	
Center	357_CIBMA_PIF_01_0178.fit	0.242	492.96293	537.35813	-1.04	1.121	Center
Upper right	357_CIBMA_PIF_01_0414.fit	0.211	935.96541	959.35347	-0.539	0.618	Corner 1
Lower right	357_CIBMA_PIF_02_0235.fit	0.238	914.13311	93.232436	-0.538	1.622	Corner 2
Upper left	357_CIBMA_PIF_02_0481.fit	0.218	72.321702	979.01759	-1.542	0.622	Corner 3
Lower left	357_CIBMA_PIF_02_0723.fit	0.265	51.862709	117.10764	-1.54	1.62	Corner 4

300 ms exposure	delta pixels	delta radians	IFOV in urad	focal length in mm
				0.000024/(IFOV*10^6)
c-ul	609.92	0.012354	20.2547	1.18491151
ul-ur	863.87	0.017506	20.2644	1.18434167
lr-ur	866.40	0.017523	20.2253	1.18663411
ll-lr	862.60	0.017488	20.2738	1.1837924
c-ur	611.83	0.012391	20.2520	1.18506648
ul-lr	1221.99	0.024732	20.2392	1.18581962
ul-ll	862.15	0.017418	20.2034	1.18791957
ur-ll	1221.07	0.024720	20.2443	1.18552122
c-lr	612.07	0.012378	20.2237	1.18672611
c-ll	609.25	0.012329	20.2365	1.18597558

	IFOV in urad	focal length in	width of FOV, deg.
			(focal length *1024 pixels*180/pi/10^6)
mean	**20.2417**	**1.18567083**	**1.18760079**
st dev	**0.020882655**	**0.0012235**	**0.0012252**

FILTER 8

Position	Filename	1x1frac	5x5ctrX	5x5ctrY	AX1	AX2	Position
Center	357_CIBMA_PIF_01_0203.fit	0.144	493.16321	537.63979	-1.04	1.121	Center
Upper right	357_CIBMA_PIF_01_0442.fit	0.135	934.07121	959.67312	-0.541	0.622	Corner 1
Lower right	357_CIBMA_PIF_02_0254.fit	0.158	913.08603	94.523854	-0.539	1.621	Corner 2
Upper left	357_CIBMA_PIF_02_0497.fit	0.136	72.838419	981.11293	-1.541	0.62	Corner 3
Lower left	357_CIBMA_PIF_02_0743.fit	0.151	51.879597	117.53428	-1.54	1.619	Corner 4

600 ms exposure	delta pixels	delta radians	IFOV in urad	focal length in mm 0.000024/(IFOV*10^6)
c-ul	611.02	0.012366	20.2384	1.18586313
ul-ur	861.50	0.017453	20.2592	1.18464564
lr-ur	865.40	0.017436	20.1477	1.19120539
ll-lr	861.51	0.017471	20.2791	1.18348165
c-ur	610.34	0.012317	20.1801	1.18929291
ul-lr	1221.50	0.024720	20.2372	1.18593485
ul-ll	863.83	0.017436	20.1843	1.18904502
ur-ll	1219.61	0.024633	20.1976	1.188259
c-lr	610.48	0.012354	20.2360	1.18600635
c-ll	609.28	0.012317	20.2152	1.18722609

	IFOV in urad	focal length in	width of FOV, deg. (focal length *1024 pixels*180/pi/10^6)
mean	**20.2175**	**1.187096**	**1.18617808**
st dev	**0.040129719**	**0.00235714**	**0.00235445**

FILTER 9

Position	Filename	1x1frac	5x5ctrX	5x5ctrY	AX1	AX2	Position
Center	357_CIBMA_PIF_01_0219.fit	0.1598	493.13049	538.34362	-1.039	1.119	Center
Upper right	357_CIBMA_PIF_02_0035.fit	0.1485	936.94907	956.86029	-0.538	0.622	Corner 1
Lower right	357_CIBMA_PIF_02_0285.fit	0.1717	914.21312	93.425714	-0.538	1.622	Corner 2
Upper left	357_CIBMA_PIF_02_0515.fit	0.1515	75.766474	981.04668	-1.5338	0.618	Corner 3
Lower left	357_CIBMA_PIF_02_0772.fit	0.1673	50.824613	117.16506	-1.541	1.62	Corner 4

900 ms exposure	delta pixels	delta radians	IFOV in urad	focal length in mm 0.000024/(IFOV*10^6)
c-ul	608.42	0.012290	20.1993	1.18815862
ul-ur	861.52	0.017380	20.1737	1.18966606
lr-ur	863.73	0.017453	20.2068	1.18772033
ll-lr	863.71	0.017506	20.2679	1.18413934
c-ur	610.03	0.012317	20.1905	1.18867523
ul-lr	1221.01	0.024680	20.2131	1.18734794
ul-ll	864.24	0.017489	20.2358	1.18601581
ur-ll	1220.78	0.024695	20.2289	1.18641962
c-lr	612.59	0.012391	20.2269	1.18653967
c-ll	610.76	0.012378	20.2672	1.18417957

	IFOV in urad	focal length in	width of FOV, deg. (focal length *1024 pixels*180/pi/10^6)
mean	**20.2210**	**1.18688622**	**1.18638601**
st dev	**0.030814671**	**0.00180809**	**0.00180793**

FILTER 10

Position	Filename	1x1frac	5x5ctrX	5x5ctrY	AX1	AX2	
Center	357_CIBMA_PIF_01_0255.fit	0.220	494.08578	537.20038	-1.038	1.121	Center
Upper right	357_CIBMA_PIF_02_0051.fit	0.157	933.24736	958.12594	-0.542	0.621	Corner 1
Lower right	357_CIBMA_PIF_02_0309.fit	0.185	913.26828	93.081146	-0.539	1.622	Corner 2
Upper left	357_CIBMA_PIF_02_0538.fit	0.186	74.14281	980.96314	-1.54	0.618	Corner 3
Lower left	357_CIBMA_PIF_02_0804.fit	0.203	52.804326	116.19656	-1.539	1.621	Corner 4

900 ms exposure	delta pixels	delta radians	IFOV in urad	focal length in mm 0.024/(IFOV*10^6)
c-ul	610.96	0.012403	20.3008	1182.22152
ul-ur	859.41	0.017418	20.2680	1184.1348
lr-ur	865.28	0.017471	20.1910	1188.64621
ll-lr	860.77	0.017453	20.2763	1183.65015
c-ur	608.31	0.012292	20.2069	1187.71284
ul-lr	1221.67	0.024744	20.2546	1184.91336
ul-ll	865.03	0.017506	20.2370	1185.94395
ur-ll	1218.21	0.024646	20.2311	1186.29116
c-lr	610.70	0.012341	20.2085	1187.61887
c-ll	609.90	0.012354	20.2554	1184.87072

	IFOV in urad	focal length in	width of FOV, deg. (focal length *1024 pixels*180/pi/10^6)
mean	**20.2430**	**1185.60036**	**1.18767335**
st dev	**0.034519664**	**2.02159198**	**0.0020253**

Summary

Filter	Bandpass/nm	IFOV in urad	Std. Dev.	FOV in deg.	Std. Dev
1	660	20.234	0.028524411	1.187	0.00167355
6	610	20.244	0.033705475	1.188	0.00197753
7	650	20.242	0.020882655	1.188	0.0012252
8	690	20.217	0.040129719	1.186	0.00235445
9	730	20.221	0.03081467	1.186	0.00180793
10	770	20.243	0.034519664	1.188	0.0020253
		20.234	0.078	1.187	0.002

Ensquared Energy

For EE, we used the point source centered in the CCD, and optimized exposure times. In the 5x5 box, the image with the brightest (best centered) central pixel was used. The fraction of light in the central pixel relative to surrounding pixels was ratioed to the integral of the surrounding 5x5 pixel box. EE for all 10 of the CFI filters were determined from the CFCCC_PIF test, and for Filters 1 and 6-10 for CRISP in CIBMA_PIF.

CFI EE ranged from 0.24 to 0.37 fraction/DN (Figure 3). CRISP EE was 0.14 to 0.26 in spectral filters, 0.33 for the clear filter (Figure 4). Table 3 shows the data used for EE calculations.

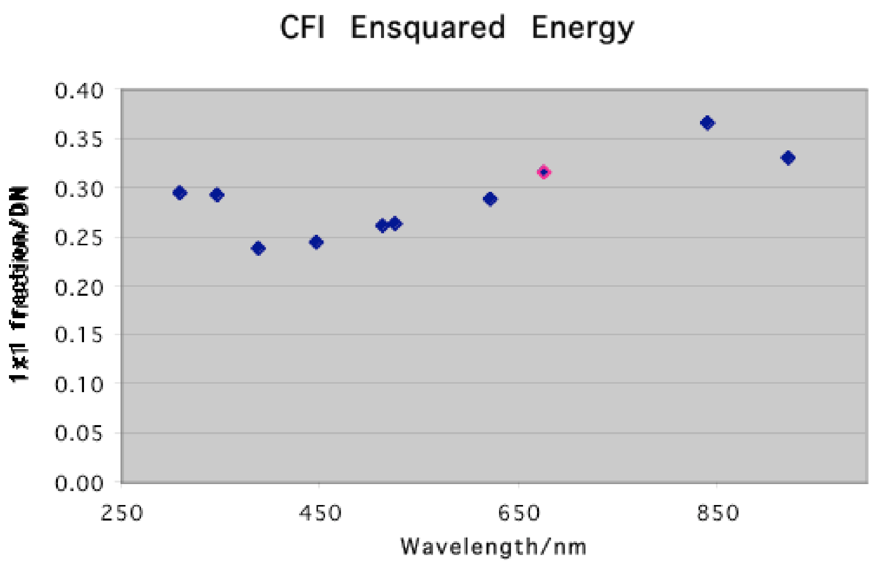

Fig. 3. Ensquared Energy, in fraction of maximum brightness/DN, for all CFI filters. Clear filter is in red.

Table 3. Data for CFI ensquared energy calculations.

CFI ENSQUARED ENERGY

CFIfinal_CFCCC_PIF

Filter #	Center wvln	Exp. time	Position	Filename	1x1frac	5x5ctrX	5x5ctrY
	nm	ms			brightest pixel	pixel	pixel
1	675	20.48	Center	52_CFCCC_PIF_03_0047.fit	0.31683401	514.93	508.95
2	920	22.528	Center	52_CFCCC_PIF_03_0090.fit	0.33001757	516.09	510.02
3	840	22.528	Center	52_CFCCC_PIF_03_0104.fit	0.36651242	514.95	508.97
4	620	26.624	Center	52_CFCCC_PIF_03_0126.fit	0.28946528	514.14	509.04
5	445	65.536	Center	52_CFCCC_PIF_03_0142.fit	0.24558007	514.94	507.90
6	526	36.864	Center	52_CFCCC_PIF_03_0169.fit	0.26429010	514.95	507.95
7	513	28.672	Center	52_CFCCC_PIF_03_0195.fit	0.26254526	516.14	507.93
8	309	831.488	Center	52_CFCCC_PIF_03_0217.fit	0.29487784	514.90	508.02
9	345	280.576	Center	52_CFCCC_PIF_03_0242.fit	0.29245961	514.93	507.92
10	387	260.096	Center	52_CFCCC_PIF_03_0278.fit	0.23772707	514.94	509.07

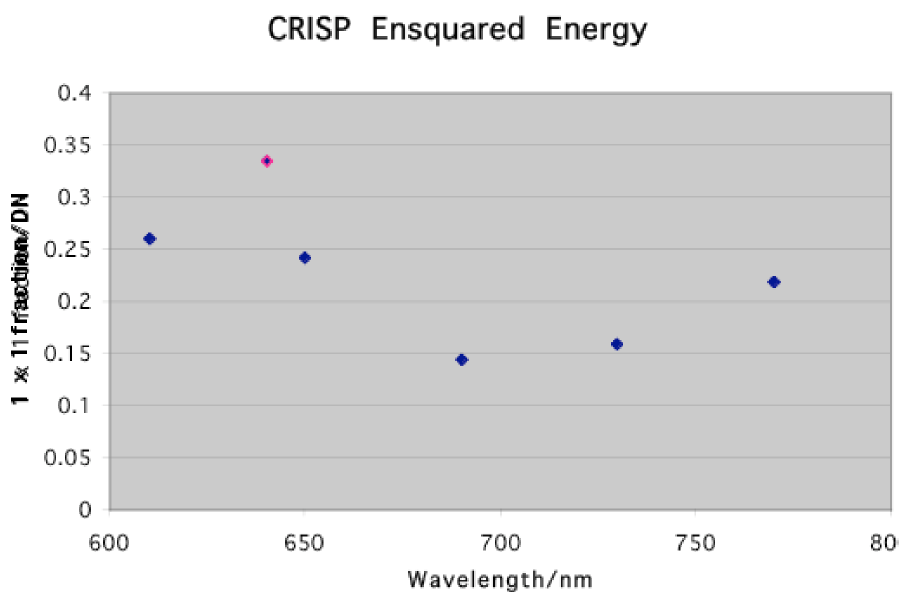

Fig. 4. Ensquared Energy, in fraction of maximum brightness/DN, for CRISP clear filter (red) and spectral filters 6-10.

Table 4. Data for CRISP ensquared energy calculations.

CRISP ENSQUARED ENERGY

CRISP Post Env. CIBMA_PIF

Filter #	Center wvln	Exp. time	Position	Filename	1x1 frac	5x5ctrX	5x5ctrY
	nm	ms			brightext pixel	pixel	pixel
1	640	10.11	Center	357_CIBMA_PIF_01_0031.fit	0.336	490.98864	535.92115
6	610	300.03	Center	357_CIBMA_PIF_01_0156.fit	0.261	491.14855	536.39497
7	650	300.03	Center	357_CIBMA_PIF_01_0178.fit	0.242	492.96293	537.35813
8	690	600.06	Center	357_CIBMA_PIF_01_0203.fit	0.144	493.16321	537.63979
9	730	900.09	Center	357_CIBMA_PIF_01_0219.fit	0.160	493.13049	538.34362
10	770	900.09	Center	357_CIBMA_PIF_01_0255.fit	0.220	494.08578	537.20038

Point Spread Function

The PSF analysis used the same 5 x 5 grid of sub-pixel dithers in all possible imager filters. For some filters, data taken in pairs with ND3, ND0, with background subtracted, and frame transfer smear corrected. Additional correction for un-removed dark current was applied from averages over boxes to left and right in same image row. The pixel containing highest fraction of light in central pixel was determined (in ND3 image if appropriate); all data was normalized to unity for the value in that pixel.

For the “Inner zone”, we took a horizontal profile across the central pixel. For the “Medial zone”, we used one of two methods, depending on available data. The preferred method was to take the average all 25 ND0 images, divided by 1000. The alternative method was to simply take the average of all 25 available images. In most cases there is a gap between the medial and distal zone, for which we must assume a form of the PSF and extrapolate out.

For CFI, The PSF for all filters are similar, possibly broader in filters 8 and 9 (Figures 5 and 6). Attenuation of brightness in CFI is approximately log-linear. For CRISP, attenuation is also approximately log-linear, but the PSF appears to broaden with increasing wavelength (Figures 7 and 8).

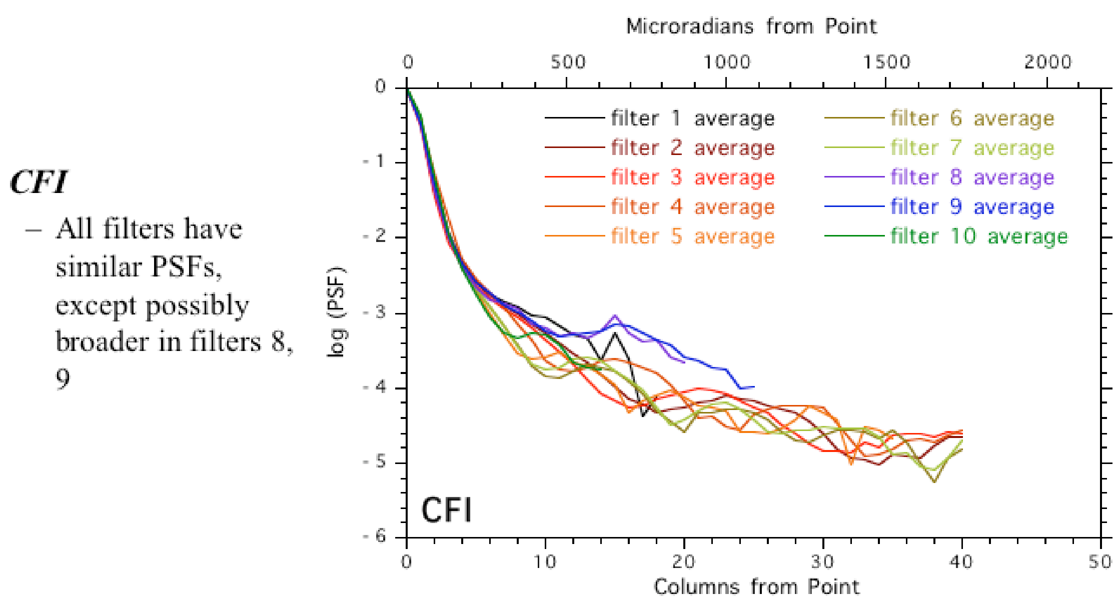

Fig. 5. This plot shows log (PSF) for all CFI filters as a function of distance from the central bright point. Filters 8 and 9 appear broader than the others with a slight ‘halo’ at 14-16 pixels distance from the center of brightness.

CFI

– Approximately linear relationship of log attenuation and log distance

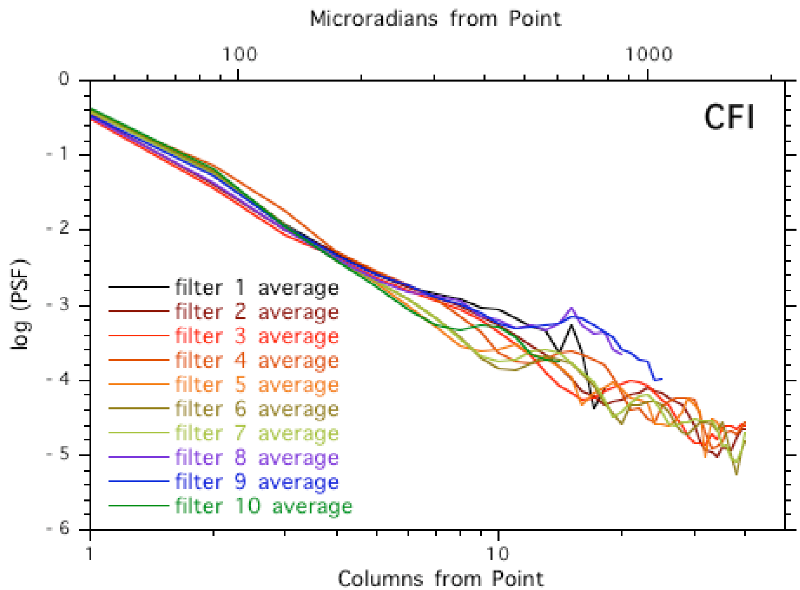

Fig. 6. This plot shows the same data as Fig. 5, but with distance from bright point in columns expressed in log space. Attenuation is approximately log-linear, with the possible exception of filters 8 and 9.

CRISP

– PSF appears to broaden with increasing wavelength

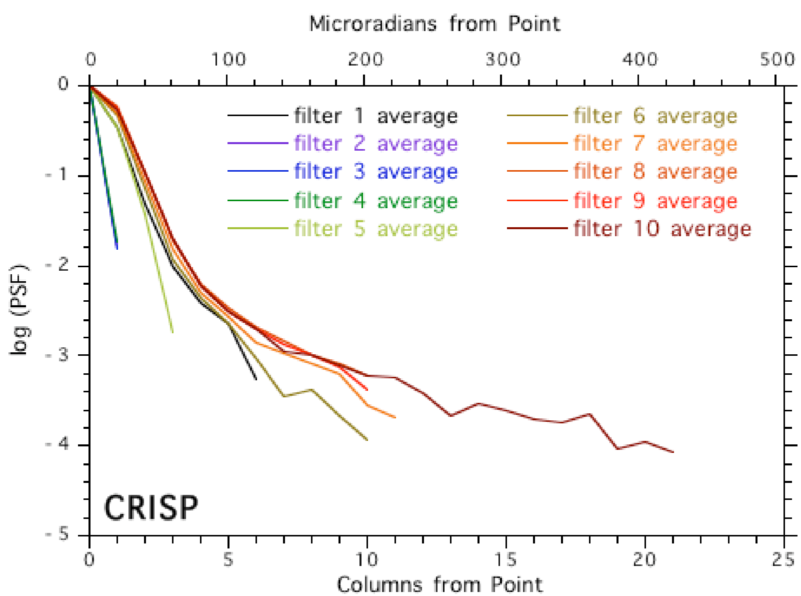

Fig. 7. CRISP PSF appears to broaden with increasing wavelength.

CRISP

- Approximately linear relationship of log attenuation and log distance

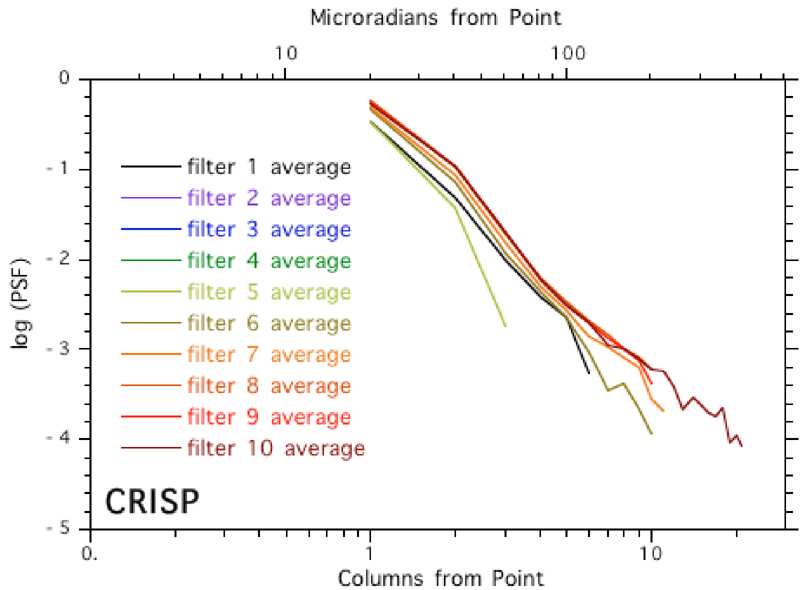

Fig 8. This plot shows the same data as Fig. 7, with column distance from bright point in expressed in log space. Attenuation is approximately log-linear.

Conclusions

IFOV, EE, and PSF for CRISP and CFI were acceptable. In-flight calibrations were planned to update and supplement the results of the on-ground calibrations.

____

Noam R. Izenberg

Distribution:

B. L. Gotwols
D. C. Humm
R.W. McEntire
S. L. Murchie
J. W. Warren
SRP Files
Archives