Comment on operational definition of CS5
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To correctly go from (x,y,z) space (e.g. FVC pixels) to positioner coordinates (e.g. Q,S), we must first align that (x,y,z) space as nearly as possible to the CS5 coordinate system. We therefore need a procedural definition of CS5 using tangible measured values. This note offers one suggestion.

In late 2017/early 2018, we did repeatability tests on mounting of petals into the focal plate integration ring. These data are captured in the sheet "repeatability of petal positions" in DESI-3542. The summary is pasted below:

ALL PETALS - REPEATABILITY OF MOUNTING TO FPR					
	diff Z			rad B - rad A	tang B - tang A
TB0_Z	0.017		TB0_Y	0.003	0.005
	0.018			0.001	0.001
	0.012			0.002	0.001
	0.004			0.002	0.007
	0.003			0.001	0.006
	0.059			0.012	0.002
TB1_Z	0.001		TB1_Y	0.007	0.139
	0.003			-0.001	0.012
	0.003			0.004	0.127
	0.002			0.001	0.135
	0.002			0.000	0.127
	0.004			0.004	0.015
TB2_Z	0.000		TB2_Y	0.003	0.138
	0.004			-0.001	0.009
	0.003			0.004	0.128
	0.002			0.001	0.136
	0.001			0.000	0.128
	0.004			0.004	0.010
max	**0.059**		**max**	**0.012**	**0.139**
min	**0.000**		**min**	**-0.001**	**0.001**
rms	**0.016**		**rms**	**0.004**	**0.088**
mean	**0.008**		**mean**	**0.003**	**0.063**
stdev	**0.014**		**stdev**	**0.003**	**0.064**

These data are for the three tooling balls (TB0, TB1, and TB2) at three far corners of each petal. So they are very good datums for measuring repeatability of placement. The key results are:

- radial repeatability: 4 um RMS, 12 um max
- tangential: 88 um RMS, 139 um max

- along z axis: 16 um RMS, 59 um max

Note the extremely good radial repeatability of petal mounting.

Regarding absolute radial position of petals, the values are given below for the two relevant metrology runs (2017-11-22 Run 2 and 2018-01-25 Run 4). Measured radial position of tooling balls when petals are assembled into the FPR, is compared against radial positions of those same balls in the individual petal coordinate sytems.

"meas" → These are in a unified CS5 system defined by the ***FPR*** tooling balls. (Note that later on, we aligned the FPR system to the ***FPD*** system, which was generated by FNAL when they aligned the corrector barrel. The FPD-FPR alignment at LBNL was within 22 um max of FNAL's definition of the optical axis.)

"ZBF" → These are in a petal coordinate system defined by Zeiss when they surveyed the 500 holes on each individual petal. ZBF is a least squares fit of all 500 holes to the nominal petal (defined in DESI-0530). ZBF is the system in which we reported all FIF and GIF measurements done at LBNL.

	2018-01-25 (run 4)			2017-11-22 (run 2)			mean of the runs		
petal id	TB0 r meas - r ZBF	TB1 r meas - r ZBF	TB2 r meas - r ZBF	TB0 r meas - r ZBF	TB1 r meas - r ZBF	TB2 r meas - r ZBF	TB0 r meas - r ZBF	TB1 r meas - r ZBF	TB2 r meas - r ZBF
-	mm	mm	mm	mm	mm	mm	mm	mm	mm
0				0.017	0.012	0.019	0.017	0.012	0.019
1				-0.006	-0.037	-0.016	-0.006	-0.037	-0.016
2	-0.053	-0.107	-0.065	-0.056	-0.115	-0.068	-0.055	-0.111	-0.067
3	0.006	0.016	0.016	0.005	0.016	0.017	0.006	0.016	0.017
4	0.003	-0.041	-0.008	0.000	-0.044	-0.012	0.002	-0.043	-0.010
5	0.016	0.012	0.020	0.014	0.011	0.020	0.015	0.011	0.020
6	0.055	-0.022	0.011	0.054	-0.022	0.011	0.054	-0.022	0.011
7	0.061	0.040	0.051	0.049	0.036	0.047	0.055	0.038	0.049
8	0.060	0.049	0.062				0.060	0.049	0.062
9	0.027	0.049	0.034				0.027	0.049	0.034
10	0.038	0.014	0.031				0.038	0.014	0.031
11	0.043	0.009	0.029				0.043	0.009	0.029
						MAX	0.060	0.049	0.062
						MIN	-0.055	-0.111	-0.067
						RMS	0.038	0.044	0.036
						MEAN	0.021	-0.001	0.015
						MEDIAN	0.022	0.012	0.020

ABSOLUTE MEASURED RADIAL POSITIONS...

	2018-01-25 (run 4)			2017-11-22 (run 2)			mean of the runs		
petal id	TB0 r meas	TB1 r meas	TB2 r meas	TB0 r meas	TB1 r meas	TB2 r meas	TB0 r meas	TB1 r meas	TB2 r meas
-	mm	mm	mm	mm	mm	mm	mm	mm	mm
0				26.037	425.909	426.079	26.037	425.909	426.079
1				26.057	426.030	425.963	26.057	426.030	425.963
2	25.990	425.878	425.746	25.986	425.871	425.742	25.988	425.875	425.744
3	26.187	425.823	425.925	26.186	425.823	425.926	26.187	425.823	425.925
4	26.080	425.977	425.924	26.077	425.973	425.920	26.079	425.975	425.922
5	25.944	426.210	425.997	25.942	426.209	425.997	25.943	426.209	425.997
6	26.182	426.107	426.143	26.181	426.107	426.144	26.181	426.107	426.143
7	26.352	426.075	426.141	26.340	426.071	426.137	26.346	426.073	426.139
8	26.276	425.981	426.168				26.276	425.981	426.168
9	25.996	426.129	426.144				25.996	426.129	426.144
10	26.320	426.038	426.106				26.320	426.038	426.106
11	26.111	425.832	425.763				26.111	425.832	425.763

(These data are in the “radial position of petals” tab of “PTL-FPR Alignment Traveler.xlsx” of DESI-3542.)

An important point is that physically, the ball TB2 is quite close to the GFA on each petal. The **upper-right-most column** in the table above (“TB2 r meas – r ZBF”) states the difference between radial positions of tooling ball 2 in a global CS5 (petals mounted together in FPR) versus in local petal coordinates (as measured by Zeiss, and as used by LBNL to define fiducial position measurements).

Finally, it is noted that DESI-5421 provides FIF and GIF pinhole locations in the ZBF coordinates.

So, bearing all this in mind, my suggestion for a procedure connecting mechanical measurements to optical (in the CS5 system) is:

1. Take FVC measurement and calculate centroids.
2. Identify devices / pinholes, make a first estimate of focal plane (0,0) and angle in FVC pixel space. Suppose we call this FVC_XY_1 coordinates.
3. Calculate radial positions of all 80 GIF dots, as measured in FVC_XY_1. Call these values
4. Calculate radial positions of all 80 GIF dots, as stated in DESI-5421. Call this “CMM_PTL_XY” coordinates.
5. Shift the radial positions of the 80 dots in CMM_PTL_XY by adding the amount “TB2 r meas – r ZBF” given in the upper right column of the table above. This is a unique shift for each petal. It is our best knowledge of where petals end up radially in the focal plane when mounted. Call the coordinates of these shifted dot positions “CMM_FPR_XY”.
6. Best-fit the radial positions of the dots in FVC_XY_1 to CMM_FPR_XY. This gives (0,0) location (and scale). Call the new coordinate system FP_XY.
7. Best-fit the scaled-and-centered “#2” coordinate system to all FIF and GIF dots as defined in CMM_PTL_XY. This gives the final x0, y0, and rot values for each petal in FP_XY.