NCSX Half Period Assembly Dimensional Control Assessment

R. Ellis

May 29, 2008

Presentation Overview

- NCSX HPA Dimensional Control Overview
- Status of HPA Dimensional Control Performance
- Measurement Techniques and Uncertainties
- Possible Improvements
- Note: much thought and insight, from a number of individuals and sources, has gone into this process over the last year. There is easily enough information to warrant a ~4 hour discussion; we have less than one hour here. If necessary or desired, I am willing to go into much more detail, with those interested, at another time. At this meeting I will need to skim over some details in order to give the overview.

The Current Center of a Modular Coil Winding is to be Positioned within 1.5mm [.06in] of its Theoretical Position

NCSX
National Compact Stellarator Experiment

- This goal results from a limitation on toroidal flux in island regions.
- This tolerance applies at the end of machine assembly.
- To understand this goal, consider that the actual coil current center is a filament in space.
- Now, consider that this filament is 3mm [.12in] thick.
- Consider that the theoretical coil current center is an infinitely thin filament in space.
- When NCSX is assembled within tolerance, the filament representing the theoretical current center will lie within the 3mm thick filament representing the actual winding.
- The tolerance budget is divided between major assembly steps.
- 0.5mm [.02in] is allocated to half period assembly.

After Coil Fabrication, the Windings Cannot be Measured Directly

NCSX National Compact Stellarator Experiment

- The coil winding is a bundle of conductors that is wound into a “box” defined by the winding form and clamps.
- Clamps are adjusted, based on winding measurements, to position the current center accurately.
- A set of monuments (“conical seats”) relate points on the MCWF to the HPA global coordinate system.
  - These monuments are used to relate the measurement equipment (Romer Arm) to the HPA global coordinate system.
- After coil winding and VPI is complete, the conductor/insulation surface is no longer accessible.
  - Measure the coil windings indirectly by measuring monuments.
  - “If the monuments are in their theoritical positions in the HPA coordinate system, then the coil current centers also occupy their theoretical positions.” (within acceptable tolerance.

The Validity of Indirect Measurements of Coil Current Centers Depends on Several Assumptions and Parameters

- Measurement accuracy during winding.
- Deviations during winding.
- No movement of windings after lacing.
- No distortion during VPI and curing.

For This Discussion, “Perfect Modular Coils” are Assumed

NCSX
National Compact Stellarator Experiment

- A “Perfect Modular Coil” is one for which, if all of the monuments are in their theoretical positions in the HPA global coordinate system, the coil current centers are on their theoretical path.
- We are making this assumption for two primary reasons:
  - It is felt that “tolerance recovery” by means of coil realignment will make this assumption valid.
  - GHN direction to use this assumption as a starting point, and focus exclusively on half period assembly issues.
- Applying our philosophy of indirect measurement, our dimensional control goal for half period assembly is that the position of every monument on the half period shall be within 0.5mm [.020”] of its theoretical position.

HPA Dimensional Control Covers the Following Major Assembly Steps

- Preparation of coils for Half Period Assembly.
- Positioning and installing the “A” coil in the HPA global coordinate system.
- Positioning and installing the “B” coil in the HPA global coordinate system.
  - We are here with B1.
- Positioning and installing the “C” coil in the HPA global coordinate system.

Preparing the Coils for HPA Requires Alignment, Measurement, and "Realignment"

NCSX National Compact Stellarator Experiment

- The external coil monuments ("tooling balls") must be related to the winding monuments ("conical seats")
  - Not achieved satisfactorily prior to winding.
  - Conical seats become inaccessible during assembly.
  - Must manage coil deformation.
  - Align to conical seats to establish coordinate system, then measure tooling balls.
- Pre-measurement of tooling balls and flanges.
  - Establish tooling ball coordinates for all future assembly steps.
  - Measure flanges for pre-calculation of shims.
- Coil "realignment"
  - Rigid body transformation of measured points (tooling balls and flanges) to recover winding tolerances.
  - A mathematical process.

Align the Laser Tracker to the Conical Seats, Measure Tooling Balls and Flanges

NCSX National Compact Stellarator Experiment

- The quality of the alignment is critical to the success of this step.
  - What is an alignment?
  - What does it mean?
- The modular coils can deform significantly as a function of their supports.
  - Winding fixture (vertical, bolted)
  - HPA assembly position (horizontal)
- Before pre-measurement, a modular coil must be twisted, or "racked", into its as-wound shape to the extent possible.
  - Adjustments normal to flange
  - Gravity load of one coil
  - .005" RMS deviation on alignment to conical seats. (ALARA)

What is an Alignment?

NCSX National Compact Stellarator Experiment

- Align laser tracker / software coordinate system to the coordinate system of interest.
- Align to a set of monuments and their known coordinates.
  - "Best fit"
- Alignment deviations are due to measurement error and actual deviations of monuments.

Verisurf Alignment Report

Part Name:	030907 A1 ON WEDGE-AA
Alignment Name:	Auto Align
Coord System:	WORLD
Date:	3/9/2007

Fit Results

Name	DX	DY	DZ	3D
3D Point 1	0.009	-0.014	0.011	**0.020**
3D Point 2	0	-0.003	0.012	**0.013**
3D Point 3	-0.002	-0.004	-0.004	**0.006**
3D Point 4	-0.004	-0.003	-0.011	**0.012**
3D Point 5	-0.005	-0.003	-0.008	**0.010**
3D Point 6	-0.005	0.008	0.015	**0.017**
3D Point 7	-0.005	0.007	0.012	**0.014**
3D Point 8	0.007	0.007	-0.016	**0.019**
3D Point 9	0.005	0.005	-0.01	**0.012**
				0.0143

Fit Summary

Total Points: 9	DX	DY	DZ	3D	
Maximum Deviation:	0.009	0.008	0.015	**0.020**	
Minimum Deviation:	-0.005	-0.014	-0.016	**0.006**	
Deviation Range:	0.014	0.022	0.03	**0.014**	
Average Deviation:	0	0	0	**0.014**	
RMS Deviation:	0.005	0.007	0.012	**0.014**	0.0148
Standard Deviation:	0.006	0.007	0.012	**0.004**	

Transformation

	X	Y	Z
Translation:	-43.521	100.198	89.243
Matrix I:	-0.205	0.976	0.076
Matrix J:	-0.916	-0.218	0.335
Matrix K:	0.344	-0.001	0.939

RMS Deviation is a Good Indicator of the Quality of an Alignment

- Usually gives a conservative estimate of deviations.
- Exceptional measurements can yield deceptively good results.
  - Not likely to happen.
- An alignment to a coil should be representative of the coil.
  - Operator judgment is required.
- To zero order, the RMS deviation indicates the positional accuracy of a point on the MCWF.

point	dx	dy	dz	3D
1	0.012	0.000	0.000	0.012
2	-0.003	0.000	0.000	0.003
3	-0.003	0.000	0.000	0.003
4	-0.003	0.000	0.000	0.003
5	-0.003	0.000	0.000	0.003
Average	0.000	0.000	0.000	0.005
RMS	0.006	0	0	0.006
Standard	0.007	0.000	0.000	0.004

Managing Modular Coil Deformation

- When taken from the winding fixture and placed horizontally, the modular coils can distort several times the magnitude of our tolerance goal.
- We have developed a procedure to adjust the deformations normal to the flanges so that the positioning of the conical seats in this direction matches the positioning as measured relative to a flange datum during winding.
  - Deformations in plane parallel to flanges cannot, practically, be changed.
  - Mathematical logic of racking procedure is presented in HPA DCP.
  - Proven in practice.
  - RMS deviation of alignment, and analysis of z-deviations in alignment report, indicates quality of racking.
- "A" coils are racked to begin HPA; proper shims maintain shape of "B" and "C" coils.

Some Self-Checking is Inherently Part of the Racking Procedure

NCSX National Compact Stellarator Experiment

- Laser measurements are used to determine adjustments.
- Adjustments are measured using dial indicators.
- Process converges to within ~.001”-.002”
  - Accuracy of convergence is limited by stiffness of the coil as well as measurement uncertainty.

Pre-Measurement of Flanges and Monuments Follows Alignment

- Establish a network of global monuments attached to building.
  - Use for relocating laser tracker.
  - Use for resuming work after equipment is powered down overnight or inadvertently bumped.
- Alignment criterion for global monuments is .002” RMS deviation.
- Measure all monuments.
  - Multiple laser positions.
- Scan the appropriate flange.

Half Period Assembly Begins with Positioning the "A" Coil into the HPA Global Coordinate System

NCSX National Compact Stellarator Experiment

- First – rack coil to assure correct shape.
- Now racking to tooling balls ➔tighter alignment criterion of .003"RMS
- Why did we rack and pre-measure the "A" coil once when we will need to rack it again?
  - To bank progress already made.
  - To take that pressure off of critical path HPA assembly.
- Second – align to the "A" coil tooling balls to establish the HPA global coordinate system.
- Why are we aligning to the "A" coil when we have spoken of positioning the coil into the HPA global coordinate system?
  - Kinematic inversion – it is easier, and equivalent, to mathematically position the coordinate system onto the coil than to physically move the coil into the coordinate system.
  - We do not have this luxury on "B" and "C" coils.

Next, the "B" Coil is Added [We are here]

NCSX National Compact Stellarator Experiment

- Shims establish shape of coil and positioning in direction normal to A-B interface.
- Measure monuments on coil to verify – opportunity to correct shim thicknesses.
- Alignment calculator used for positioning "B" coil in plane of A-B interface.
- Initial shim weld → position "B" coil, torque bolts, measure, final shim weld, measure.
- Accuracy goal is .012" deviation of monuments from theoretical position.
- How did we do?
  - 78 monuments measured, 2 outliers [.014", .015"]

number of nominals = 100   number measured = 78

locations in half period coordinate system

xmeas	ymeas	zmeas	xnsrt	ynsrt	znsrt
13.721	10.652	-8.191	13.724	10.650	-8.180
22.733	-9.454	-0.954	22.738	-9.456	-0.951
15.381	-16.724	-11.801	15.389	-16.728	-11.790
18.749	-36.737	-0.964	18.751	-36.742	-0.954
29.745	-50.929	-0.954	29.746	-50.936	-0.950
28.748	-44.930	-5.770	28.745	-44.938	-5.767
28.747	-46.393	-9.462	28.748	-46.400	-9.461
25.763	-42.519	-10.306	25.768	-42.521	-10.303
45.809	-53.428	-17.608	45.812	-53.432	-17.606
31.009	-35.416	-24.903	31.014	-35.418	-24.896
40.500	-43.366	-24.811	40.504	-43.374	-24.811
50.978	-40.682	-36.111	50.982	-40.685	-36.109
59.449	-50.769	-12.912	59.453	-50.774	-12.910
65.316	-49.370	-22.759	65.320	-49.377	-22.757
64.538	-49.077	-24.428	64.544	-49.080	-24.429
102.096	-14.817	-18.710	102.096	-14.821	-18.711
88.655	0.088	-41.505	88.659	0.087	-41.508
83.987	-12.140	-48.194	83.990	-12.143	-48.197
72.723	-14.731	-59.883	72.725	-14.733	-59.886
102.748	-2.368	-20.105	102.749	-2.372	-20.105
95.207	18.810	-25.065	95.206	18.810	-25.066
97.389	32.156	-0.936	97.386	32.152	-0.932
88.249	36.073	-9.196	88.250	36.073	-9.197
84.527	36.978	-16.645	84.530	36.985	-16.648
83.912	34.527	-22.612	83.913	34.525	-22.613
89.297	26.526	-33.425	89.297	26.527	-33.428
88.247	29.432	-31.096	88.248	29.431	-31.097
80.567	38.301	-28.303	80.565	38.297	-28.304
79.693	38.134	-29.935	79.697	38.133	-29.936
77.447	12.701	-48.063	77.450	12.700	-48.064
67.180	22.973	-55.233	67.180	22.971	-55.235
62.555	28.466	-46.410	62.555	28.463	-46.411
66.161	33.780	-40.186	66.161	33.778	-40.189
57.878	35.904	-47.447	57.877	35.901	-47.448
59.745	40.234	-30.881	59.751	40.233	-30.878
56.435	50.719	-5.495	56.437	50.719	-5.499
44.970	51.891	-0.990	44.970	51.891	-0.994
57.382	51.358	-12.046	57.383	51.360	-12.051
56.732	52.829	-19.634	56.732	52.824	-19.638
55.973	52.599	-21.309	55.975	52.600	-21.313
42.735	47.706	-25.736	42.735	47.708	-25.737
42.934	46.644	-34.926	42.934	46.639	-34.926
57.383	51.359	-12.045	57.383	51.360	-12.051
42.735	47.707	-25.736	42.735	47.708	-25.737
42.934	46.645	-34.925	42.934	46.639	-34.926
24.458	44.355	-4.497	24.461	44.357	-4.493
29.741	50.927	-0.953	29.745	50.931	-0.949
27.843	50.674	-11.087	27.844	50.675	-11.091
28.282	47.016	-22.643	28.284	47.011	-22.642
24.994	48.669	-8.096	24.995	48.668	-8.098
25.776	44.144	-15.560	25.778	44.142	-15.558
20.659	41.053	-0.960	20.667	41.053	-0.952
21.482	45.669	-8.777	21.484	45.670	-8.778
16.172	34.636	-12.486	16.175	34.634	-12.480
13.721	10.652	-8.191	13.724	10.650	-8.180
22.734	-9.453	-0.956	22.738	-9.456	-0.951
15.381	-16.724	-11.800	15.389	-16.728	-11.790
18.749	-36.739	-0.963	18.751	-36.742	-0.954
40.502	-43.366	-24.811	40.504	-43.374	-24.811

45.810	-53.428	-17.607	45.812	-53.432	-17.606
46.555	-53.754	-15.934	46.555	-53.762	-15.933
44.969	-51.880	-0.943	44.970	-51.884	-0.943
59.450	-50.770	-12.911	59.453	-50.774	-12.910
54.757	-48.907	-16.256	54.759	-48.910	-16.254
65.317	-49.371	-22.758	65.320	-49.377	-22.757
64.539	-49.078	-24.427	64.544	-49.080	-24.429
60.219	-41.866	-34.468	60.222	-41.870	-34.467
50.978	-40.682	-36.110	50.982	-40.685	-36.109
56.875	-40.275	-46.600	56.878	-40.278	-46.599
83.109	-31.424	-31.072	83.114	-31.428	-31.072
67.631	-27.411	-49.001	67.633	-27.413	-49.002
97.242	-32.404	-0.937	97.247	-32.411	-0.937
93.076	-27.628	-32.848	93.078	-27.633	-32.848
90.763	-29.660	-33.957	90.770	-29.663	-33.958
72.721	-14.731	-59.883	72.725	-14.733	-59.886
83.986	-12.140	-48.195	83.990	-12.143	-48.197
102.095	-14.817	-18.710	102.096	-14.821	-18.711
102.747	-2.368	-20.105	102.749	-2.372	-20.105

locations in coordinate system normal to interface

xnomb	ynomb	znomb	xmeasb	ymeasb	zmeasb	delx	dely	delz	dels
15.694	10.650	-2.993	15.696	10.652	-3.004	0.001	0.002	-0.011	0.012
21.692	-9.456	6.884	21.688	-9.454	6.878	-0.004	0.002	-0.005	0.007
18.493	-16.728	-5.815	18.490	-16.724	-5.829	-0.004	0.004	-0.014	0.015
17.946	-36.742	5.517	17.948	-36.737	5.507	0.002	0.004	-0.010	0.011
28.277	-50.936	9.281	28.278	-50.929	9.277	0.001	0.008	-0.004	0.009
28.984	-44.938	4.412	28.988	-44.930	4.410	0.004	0.009	-0.002	0.010
30.250	-46.400	0.942	30.249	-46.393	0.941	-0.001	0.007	-0.001	0.008
27.738	-42.521	-0.868	27.734	-42.519	-0.873	-0.004	0.002	-0.005	0.007
49.071	-53.432	-0.875	49.069	-53.428	-0.878	-0.002	0.004	-0.003	0.005
37.659	-35.418	-12.787	37.656	-35.416	-12.795	-0.003	0.002	-0.008	0.009
46.547	-43.374	-9.461	46.544	-43.366	-9.463	-0.003	0.009	-0.002	0.009
60.257	-40.685	-16.495	60.255	-40.682	-16.498	-0.002	0.003	-0.004	0.005
60.283	-50.774	8.203	60.280	-50.769	8.200	-0.003	0.006	-0.003	0.007
69.164	-49.377	0.957	69.161	-49.370	0.953	-0.003	0.007	-0.004	0.009
69.007	-49.080	-0.881	69.001	-49.077	-0.882	-0.006	0.003	-0.001	0.007
102.338	-14.821	17.337	102.338	-14.817	17.337	0.000	0.003	0.000	0.003
97.509	0.087	-8.682	97.504	0.088	-8.680	-0.005	0.001	0.002	0.006
95.409	-12.143	-16.564	95.406	-12.140	-16.563	-0.003	0.003	0.002	0.004
88.821	-14.733	-31.401	88.819	-14.731	-31.399	-0.003	0.002	0.002	0.003
103.428	-2.372	16.250	103.428	-2.368	16.249	0.000	0.003	0.000	0.003
98.038	18.810	9.008	98.037	18.810	9.010	0.000	0.001	0.001	0.001
91.832	32.152	32.432	91.836	32.156	32.430	0.004	0.004	-0.002	0.006
86.073	36.073	21.541	86.072	36.073	21.542	-0.001	0.001	0.001	0.002
85.126	36.985	13.267	85.123	36.978	13.269	-0.003	-0.007	0.002	0.008
86.586	34.525	7.451	86.586	34.527	7.452	0.000	0.002	0.001	0.002
95.345	26.527	-0.870	95.343	26.526	-0.868	-0.002	0.000	0.002	0.003
93.561	29.431	0.961	93.560	29.432	0.961	-0.001	0.001	0.001	0.002
85.387	38.297	0.958	85.388	38.301	0.959	0.001	0.004	0.002	0.005
85.129	38.133	-0.873	85.126	38.134	-0.873	-0.004	0.001	0.000	0.004
89.218	12.700	-18.676	89.215	12.701	-18.676	-0.003	0.001	0.000	0.003
82.020	22.971	-28.927	82.019	22.973	-28.925	-0.001	0.003	0.003	0.004
74.656	28.463	-22.217	74.656	28.466	-22.216	0.000	0.003	0.001	0.003
75.916	33.778	-15.137	75.916	33.780	-15.134	-0.001	0.002	0.002	0.003
70.615	35.901	-24.791	70.615	35.904	-24.790	0.000	0.003	0.001	0.003
66.708	40.233	-8.580	66.704	40.234	-8.585	-0.004	0.001	-0.005	0.006
54.914	50.719	14.135	54.911	50.719	14.139	-0.003	0.001	0.003	0.004
42.598	51.891	14.447	42.596	51.891	14.451	-0.002	0.001	0.004	0.004
58.044	51.360	8.302	58.042	51.358	8.306	-0.003	-0.002	0.004	0.005
60.027	52.824	0.950	60.026	52.829	0.953	-0.002	0.004	0.003	0.005
59.888	52.600	-0.883	59.885	52.599	-0.880	-0.003	-0.001	0.003	0.004
48.960	47.708	-9.568	48.959	47.706	-9.568	-0.001	-0.001	0.001	0.002

52.290	46.639	-18.136	52.290	46.644	-18.135	0.000	0.005	0.001	0.005
58.044	51.360	8.302	58.042	51.359	8.307	-0.002	-0.001	0.006	0.006
48.960	47.708	-9.568	48.960	47.707	-9.567	-0.001	0.000	0.001	0.001
52.290	46.639	-18.136	52.290	46.645	-18.135	0.000	0.006	0.001	0.006
24.522	44.357	4.144	24.521	44.355	4.140	-0.001	-0.002	-0.005	0.005
28.276	50.931	9.282	28.273	50.927	9.277	-0.003	-0.004	-0.005	0.007
29.958	50.675	-0.899	29.956	50.674	-0.896	-0.002	0.000	0.003	0.004
34.322	47.011	-11.603	34.321	47.016	-11.604	-0.001	0.005	-0.001	0.005
26.258	48.668	0.939	26.256	48.669	0.941	-0.002	0.001	0.002	0.003
29.544	44.142	-5.803	29.543	44.144	-5.806	-0.001	0.002	-0.002	0.003
19.746	41.053	6.174	19.742	41.053	6.163	-0.004	0.000	-0.011	0.012
23.190	45.670	-0.901	23.188	45.669	-0.900	-0.002	-0.001	0.001	0.003
19.468	34.634	-6.195	19.467	34.636	-6.202	0.000	0.002	-0.007	0.007
15.694	10.650	-2.993	15.695	10.652	-3.004	0.001	0.003	-0.011	0.011
21.692	-9.456	6.884	21.689	-9.453	6.877	-0.003	0.003	-0.007	0.008
18.493	-16.728	-5.815	18.490	-16.724	-5.828	-0.004	0.004	-0.013	0.014
17.946	-36.742	5.517	17.948	-36.739	5.507	0.002	0.003	-0.009	0.010
46.547	-43.374	-9.461	46.545	-43.366	-9.462	-0.002	0.008	-0.001	0.009
49.071	-53.432	-0.875	49.069	-53.428	-0.877	-0.002	0.004	-0.002	0.004
49.197	-53.762	0.951	49.197	-53.754	0.949	0.000	0.007	-0.001	0.008
42.581	-51.884	14.494	42.579	-51.880	14.494	-0.001	0.005	0.000	0.005
60.283	-50.774	8.203	60.280	-50.770	8.201	-0.003	0.005	-0.002	0.006
57.016	-48.910	3.455	57.014	-48.907	3.452	-0.001	0.003	-0.003	0.004
69.164	-49.377	0.957	69.161	-49.371	0.955	-0.003	0.006	-0.002	0.007
69.007	-49.080	-0.881	69.001	-49.078	-0.880	-0.006	0.002	0.001	0.006
68.379	-41.870	-11.792	68.376	-41.866	-11.793	-0.003	0.004	-0.002	0.005
60.257	-40.685	-16.495	60.254	-40.682	-16.497	-0.003	0.003	-0.003	0.005
69.386	-40.278	-24.335	69.383	-40.275	-24.337	-0.003	0.003	-0.002	0.004
88.729	-31.428	-0.772	88.724	-31.424	-0.773	-0.005	0.004	-0.001	0.006
80.314	-27.413	-22.915	80.311	-27.411	-22.915	-0.003	0.002	0.000	0.004
91.703	-32.411	32.380	91.698	-32.404	32.378	-0.005	0.007	-0.002	0.009
98.700	-27.633	0.967	98.698	-27.628	0.967	-0.002	0.005	0.000	0.006
96.910	-29.663	-0.865	96.903	-29.660	-0.866	-0.007	0.003	-0.001	0.008
88.821	-14.733	-31.401	88.816	-14.731	-31.400	-0.005	0.002	0.001	0.005
95.409	-12.143	-16.564	95.405	-12.140	-16.564	-0.004	0.002	0.000	0.005
102.338	-14.821	17.337	102.337	-14.817	17.337	-0.001	0.004	0.000	0.004
103.428	-2.372	16.250	103.427	-2.368	16.249	-0.001	0.004	-0.001	0.004

xavg = -0.0019 yavg = 0.0028 zavg = -0.0016 savg = 0.0058
xstd = 0.0020 ystd = 0.0028 zstd = 0.0040 sstd = 0.0028

Finally, the "C" coil is added [in process]

- The same general steps as the A-B assembly are followed.
- Intermediate measurements to date are encouraging.
- Accuracy goal is .020" maximum deviation of monuments from theoretical positions.

Coil Distortion and Measurement Uncertainty is Introduced Throughout the Process

- Our assembly process and dimensional control plan attempt to minimize both.
- Different measurement techniques have different levels of uncertainty, and different degrees of applicability to specific tasks.

Blunders, Systemic Errors and Random Errors are the Sources of Measurement Error

NCSX National Compact Stellarator Experiment

- "Blunders" are mistakes in either making, or recording, measurements, and are usually obvious.
  - Correct blunders, where possible, before processing data.
- Systemic errors are errors inherent to equipment, and can in theory be compensated for during data analysis.
  - Examples – thermal expansion of a scale bar, thermal expansion of components to be measured.
  - In our case, these are smaller than our random errors.
- Random errors result from random variations in a process or measurement technique.
  - Define confidence intervals on measurements that are subject to random variation.

Laser Measuring Tools

- Corner cube
  - 1.5” or .5” diameter.
  - Sits in magnetic nest.
  - .5” diameter, with special nest, mimics short shank tooling ball.
  - Negligible positioning accuracy relative to nest.
  - Global monuments are 1.5”dia corner cube, in nest that is secured to building or HPA fixture.
  - When nest is placed in tooling ball hole, the accuracy issues are the same as for a tooling ball – tightness of the hole.
  - Possible blunders using the .5”diameter corner cube and special nest – does it remain seated in hole after grip is released? [air pressure in hole may act as spring] ~.001” - .002” effect; difficult to recognize
  - Limited viewing angles

Laser Measuring Tools

- Leica Surface Reflector
  - Allows the laser to measure to the center of a tooling ball by creating a virtual center.
  - Avoids the problem of a tooling ball or nest “releasing” during measurement.
  - Limited view angles.
  - Highly accurate.

Laser Measuring Tools

- Measure a sphere around a tooling ball (or 15mm ball bearing in a conical seat) using a corner cube, in a nest, on a wand.
- Best view, least accurate.
- Was necessary for measuring conical seats.
- Qualification tests performed to assess accuracy of this technique.
- In-field checking of sphericity of measurement helps to eliminate blunders.

Some Thoughts on Confidence Intervals

- For a process with a normal distribution, we can define confidence intervals as ratios of the standard deviation
  - Some [two-sided] ratios:
    - 50% -> .67; 75% -> 1.15; 90% -> 1.65; 95% -> 1.96; 99% -> 2.58
  - For a standard deviation of .0006in for any component of a measurement, the confidence intervals become:
    - 50% -> .0004"; 75% -> .0007"; 90% -> .001"; 95% -> .0012"; 99% -> .0015"
- If we have a normally distributed population N(μ,σ) of measurements , and we take samples of n measurements, then the means of the samples will also be normally distributed.

$$\bar{x} = N\left(\mu, \sigma/\sqrt{n}\right)$$

- The effective standard deviation is reduced. For our superpoints(n=100), by one order of magnitude. For "Dan-O" points (n=50) by ~7.

Some Thoughts on Confidence Intervals

- How do the confidence intervals on the components affect the 3-d deviation?
- Let α, β, γ represent the magnitude of expected error, or half the confidence interval, in the x, y, and z measurements respectively.
- The radius of the "error sphere" representing the 3-d deviation is then
  $\varepsilon = \sqrt{3}\sigma$
- For a 99% confidence interval and σ=.0006in, we have
  - Single point -> .0013"
  - "Dan-O" point -> .00019
  - Super point ->.00013
  - Scepter Sphere -> .0044

Standard Deviation of Measurements is Obtained from Qualification Tests

- Use the square root of variance as an unbiased estimator for the standard deviation.
- Place a confidence interval on the estimate of the variance, then use the upper end of that interval.

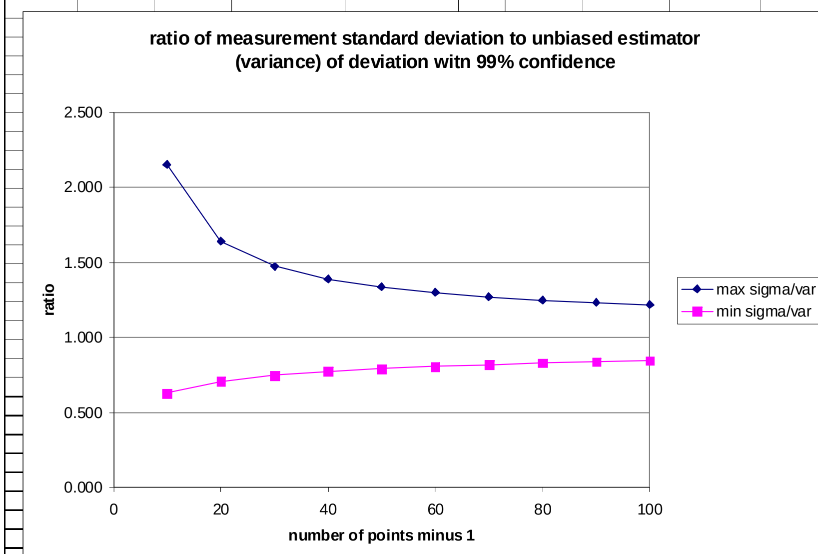
$$\chi_{.005}{}^2 \le \frac{(n-1)s^2}{\sigma^2} \le \chi_{.995}{}^2$$

Worksheet for estimating measurement standard deviation based on a sample of measurements

n-1	chisq.005	chisq.995	chisq.005/(n-1)	chisq.995/(n-1)	ratio		min 1/sig^2	max 1/sig^2	min sigma	max sigma	max(sigma/var)	min(sigma/var)
10	2.160	25.200	0.216	2.520	11.67		96000	1120000	0.0009	0.0032	2.152	0.630
20	7.430	40.000	0.372	2.000	5.38		165111	888889	0.0011	0.0025	1.641	0.707
30	13.800	53.700	0.460	1.790	3.89		204444	795556	0.0011	0.0022	1.474	0.747
40	20.700	66.800	0.518	1.670	3.23		230000	742222	0.0012	0.0021	1.390	0.774
50	28.000	79.500	0.560	1.590	2.84		248889	706667	0.0012	0.0020	1.336	0.793
60	35.500	92.000	0.592	1.533	2.59		262963	681481	0.0012	0.0020	1.300	0.808
70	43.300	104.000	0.619	1.486	2.40		274921	660317	0.0012	0.0019	1.271	0.820
80	51.200	116.000	0.640	1.450	2.27		284444	644444	0.0012	0.0019	1.250	0.830
90	59.200	128.000	0.658	1.422	2.16		292346	632099	0.0013	0.0018	1.233	0.839
100	67.300	140.000	0.673	1.400	2.08		299111	622222	0.0013	0.0018	1.219	0.845

Unbiased Estimated Standard Deviation

0.0015



Where are we now, assuming 99% confidence intervals?

- Alignment to a modular coil – same as RMS deviation
  - .005” when we achieve our goal.
- Pre-measurement uncertainty - .0059”
  - .0044 measurement uncertainty from sphere + .0015 for global alignment.
- Our measurement uncertainty after A1B1 - .0034”
  - .0015 for global alignment + .0019” “Dan-O” uncertainty.
- .0143” total.
- This is not expected to change after C1 is added to A1B1, because the uncertainties are not directly additive.

Is our performance really at the “top of error bar” level?

- Convergence of racking process indicates that measurements with scepter are better than the extreme end of error bar.
- The use of pre-calculated shims, and adjustment of shims based on laser measurements, has worked to a greater accuracy than that indicated by the extremes of a 99% confidence interval.
- Horizontal position adjustments using the alignment calculator perform better than what we would obtain if our measurements were at the extremes of a 99% confidence interval.

Some caveats and thoughts for future discussion…

NCSX
National Compact Stellarator Experiment

- On the early modular coils (the ones we are presently assembling) we did not preserve the conical seats prior to pre-measurement. We therefore had to rack, and align, to measurements of the tooling balls taken during initial conical seat installation, when the deformed shape of the coil was not precisely defined. The racking and alignments to these monuments did not meet our .005" criterion, and we may well have lost ~.020" of accuracy here.
- Can we make use of our large number of monuments to draw some statistical inferences, with higher accuracy/confidence, than we have now?