LAT Engineering Meeting

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LAT Preliminary Survey Results

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Outline

- Tolerance budgeting
- Grid survey results
- Tracker inspection results
- LAT survey results
- Take-aways and summary

- See also:
  - LAT-DS-00851, “TKR-LAT Interface Definition Drawing”
  - LAT-MD-00895, “LAT Survey Plan”
  - LAT-MD-03566, “Tracker Tower Assembly and Alignment Plan”
  - LAT-TD-06368, “Grid Survey Analysis Report”

All dimensions in millimeters (mm) unless expressly shown otherwise

Tolerance Budgeting

- Ensuring that there are adequate gaps between TKR modules has been a concern for a very long time
- Many things influence the size of the gap and the required minimum, including
  - Nominal dimensions and tolerances of the parts and assemblies
  - Expected relative motions of the sub-assemblies due to a variety of external influences: acoustic, accelerations, and differential expansion
  - Tolerances and precision of the assembly and inspection processes
- To simplify the development process, these factors were parsed out between the TKR and Mechanical subsystems
  - TKR-controlled influences on the TKR-TKR gap
    - Nominal module size—the nominal size increased well after the gap had been set, so tolerances had to be held tighter
    - Tolerances on module dimensions—due to a stack-up of tray and sidewall tolerances
    - Tolerances on placement of the module with respect to its interfaces—eccentric cones implemented to significantly reduce these tolerances
    - Dynamic deflection—a result of the stiffness of the module and the input acoustic loads
    - Static deflection—due to hysterisis of the bolted joint
  - Mechanical Systems-controlled influences on the TKR-TKR gap
    - Grid manufacturing—tolerances of TKR interface holes
    - Grid sag—due to launch accelerations, that cause TKR's to tip
    - Grid thermal contraction—due to changes in temperature
  - All dimensional factors were folded into LAT-DS-00851, the TKR-LAT IDD
  - Deflections were handled by specifying minimum natural frequencies
- Next step: define the limits for each of these factors…

Factors Affecting Impingement on the TKR-TKR Gap

- **TKR and Grid fab/ass'y tol's were developed with an eye toward how they impacted gap width**
  - **TKR stayclear**
    - **372.5 at top**
    - **373.5 at bottom**
  - **Pitch between towers: 374.5**
  - **Width of half-gap**
    - **1.0 mm at top**
      - **0.635 pos + 0.365 motion**
    - **0.5 mm at bottom**
      - **0.288 pos + 0.212 motion**

TKR Lateral Fit Inside its Stayclear	Sides	Washers	Top
Nominal tray width	368.500	368.500	368.500
Max Sidewall thickness (incl 0.050 thk alum foil)	1.625	1.625	1.625
Max paint thickness	0.025		
Washer + epoxy thk / single layer EMI tape on top		0.655	0.089
Estimate flatness tolerance of tower side	0.280	0.000	0.280
Tower max width	**372.360**	**373.060**	**372.488**
Tower stayclear width (LAT-DS-00851)	372.500	373.500	372.500
Pitch between TKR towers	374.500	374.500	374.500
Nominal half-gap between stay-clears	**1.000**	**0.500**	**1.000**

Impingement on Gaps Around TKR	Source of Motion +/- Tol's		Effect of Source on Impingement (+/- X or +/-Y)					
			Lateral at Top		Lateral L/O, MECO		Vertical	
	X/Y	Z	Liftoff	MECO	Bottom	Washers	L/O,MECO	Comments
A. TKR static, acoustic motion wrt nom position			*0.266*	*0.143*	*0.126*	*0.126*	*0.075*	
Module acoustic motion (module top, half-peak)	0.123	0.000	0.123	0.000	0.076	0.076	0.000	Predicted from analysis
Static hysteresis based on B.T. static test (half-peak)	0.050	0.025	0.143	0.143	0.050	0.050	0.075	Expected max set of module
B. TKR alignment accuracy and measure precision			*0.188*	*0.188*	*0.040*	*0.040*	*0.120*	
Alignment accuracy of eccentrics	0.015	0.015	0.071	0.071	0.015	0.015	0.045	Based on TKR tests
Alignment measurement precision	0.025	0.025	0.118	0.118	0.025	0.025	0.075	CMM precision
C. Grid tolerances			*0.366*	*0.366*	*0.181*	*0.181*	*0.150*	
Grid bay datum pins wrt neighboring bay	0.075		0.075	0.075	0.075	0.075		True position to 0.15
Grid stud hole positions wrt bay datum pins	0.075	0.050	0.106	0.106	0.106	0.106	0.150	Mach errors in Grid holes
TKR tipping at top due to Grid hole angle wrt Grid			0.185	0.185				Due to Grid corner hole Z-tol
D. CLA, Thermal dynamic motion wrt nom position			*0.019*	*0.264*	*0.019*	*0.019*	*1.369*	
TKR module top swing due to tip from Grid sag				0.245			0.500	
Bay-to-bay motion due to 5 degC dTemp at launch	0.019	0.024	0.019	0.019	0.019	0.019	0.024	Launch vs ass'y temp
ACD vertical drumhead motion relative to base		0.845					0.845	
E. Total impingement on half-gap (simple sum)			0.839	0.961	0.366	0.366	1.714	
F. Nom half-gap between stay-clears			1.000	1.000	1.000	0.500	7.400	
G. Margin on integrated TKR-TKR half-gap			0.161	0.039	0.634	0.134	5.686	
Max allowed position tolerance of TKR Stayclear on Grid (B+C+margin/2)			0.635	0.574	0.538	0.288		

Source: "Tolerances—2005-06-23" spreadsheet

Measuring the Hardware to Determine if Factors are Controlled

- The LAT survey program details the process by which the manufacturing- and interface-related factors are measured to ensure that they are within the allowed limits
- There are three steps to this
  - Surveying the Grid (LAT-MD-00895, "LAT Survey Plan")
    - A Grid Coordinate System (GCS) was established to define the center of the Grid
    - The LAT Coordinate System (LCS) is orthogonal to the GCS, with a simple Z-offset up to the top flange of the Grid
    - All TKR interface holes were inspected
    - These as-built hole locations were used to define 16 Bay Coordinate Systems (BCS)
    - A BCS is nominally located at the center of a bay, orthogonal to the GCS, but errors in hole positioning result in offsets and tilting of the BCS, which in turn impact TKR positioning
  - Surveying and aligning the TKR tower (LAT-MD-03566, "Tracker Tower Assembly and Alignment Plan")
    - The TKR towers are inspected by CMM in Pisa after they are constructed
    - Based on the actual size of the tower, a Tower Coordinate System (TCS) is constructed for each
    - The TCS defines the ideal center/orientation of the actual tower, so its footprint is minimized
      - This corrects for any individual feature out-of-tolerance conditions
      - The TCS accommodates and adjusts for any systematic mis-shaping of the tower, including racking, bowing, and twisting
    - Finally, with the ideal center defined, the eccentric cones are used to place the TKR interface holes in their correct location with respect to the tower ideal center (the TCS origin)
  - Surveying TKR's on the LAT (LAT-MD-00895, "LAT Survey Plan")
    - Finally the TKR's are surveyed in their final location on the LAT
    - The location of the TKR TCS is established with respect to the GCS
    - The offset of the TCS is then compared to the allowed position tolerance to determine if the module is integrated within tolerance

Grid Survey Results

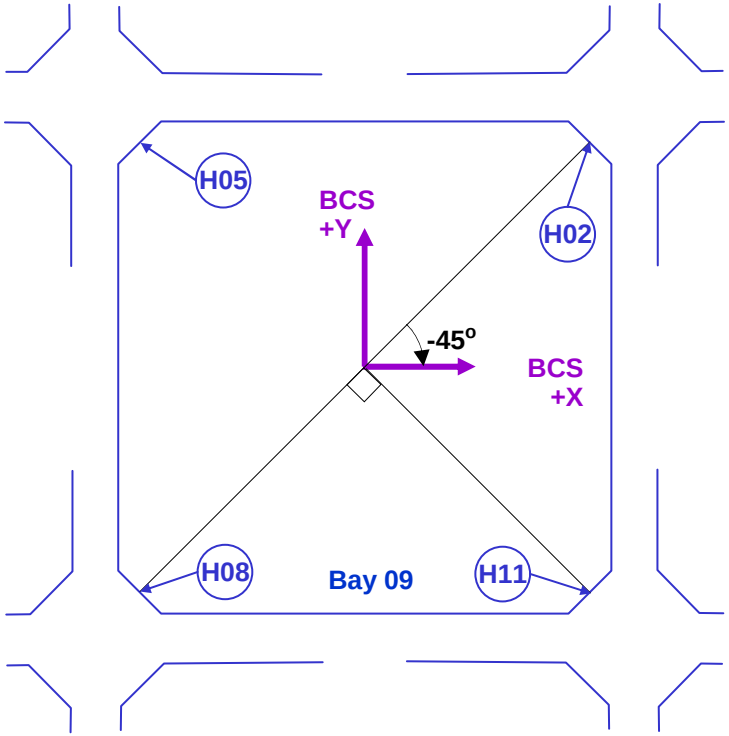
- LAT-TD-06368, "Grid Survey Analysis Report" provides a complete description of the surveying and analysis of Grid dimensional inspection data—including TKR interfaces, Spacecraft interfaces, and Grid features
- The following is a precis of the report as related to the TKR interface

- TKR interface holes on the Grid
  - Each TKR is mounted at 16 points around a bay of the Grid
  - Of these 16 locations, only 3 of the 4 corner locations are used for positioning the TKR
  - The holes on the Grid were toleranced such that even with a systematic offset of all holes to the maximum of the tolerance, the Grid could still be used
- TKR interface hole inspection results
  - 49 out of 64 corner holes in the Grid are out of tolerance
  - 9 out of 64 corner holes are out of the planarity tolerance
- However, what matters is not the individual hole location, but the location and attitude of the BCS as defined by the 3 corner holes. A few predictions:
  - If the hole errors were random, then the BCS origin should still be close to nominal, even though the individual holes are out of tolerance
  - Given the machining set-up, the holes should all be close to parallel to the Grid GCS, which means that the BCS Z-axis should not be tipped much; if all 3 corner holes in a given bay are parallel to the GCS, their average height is less important

- Next step: define an as-built BCS for each bay, using actual hole locations…

Bay Coordinate System Locations

- BCS origin
  - The table shows that all but 2 of the 16 BCS origins are within their allowable tolerance
  - This shows that machining errors were, indeed, random
- BCS orientation
  - There is very little tip whatsoever in the BCS Z-axis



Grid Bay Coordinate System Offsets

	BCS Ctr Delta off Nom			Angle to Grid Norm	H08-H02 Angle off 45
	dXc (mm)	dYc (mm)	dZc (mm)	dRR (deg)	dRZ (deg)
Bay 00	0.107	0.115	0.026	0.009	-0.001
Bay 01	0.124	0.071	0.002	0.002	0.009
Bay 02	0.024	-0.016	0.042	0.012	0.007
Bay 03	0.016	0.006	-0.005	0.007	0.002
Bay 04	0.037	0.047	0.025	0.011	-0.002
Bay 05	0.008	0.021	-0.032	0.009	-0.002
Bay 06	0.032	0.018	0.002	0.005	0.002
Bay 07	0.040	0.035	-0.021	0.008	0.001
Bay 08	0.108	0.034	0.032	0.026	0.013
Bay 09	0.064	0.023	0.027	0.012	0.007
Bay 10	0.091	0.045	-0.011	0.004	0.008
Bay 11	0.064	0.013	-0.006	0.002	0.009
Bay 12	0.096	0.020	0.009	0.016	0.013
Bay 13	0.085	0.034	0.006	0.018	0.009
Bay 14	0.089	0.033	0.001	0.019	0.010
Bay 15	0.079	0.023	-0.032	0.013	0.010
Max:	0.124	0.115	0.042	0.026	0.013
Tol:	0.114	0.114	0.051	0.603	

Source: "LATSurveyDataR5--2005-04-02Survey.xls"

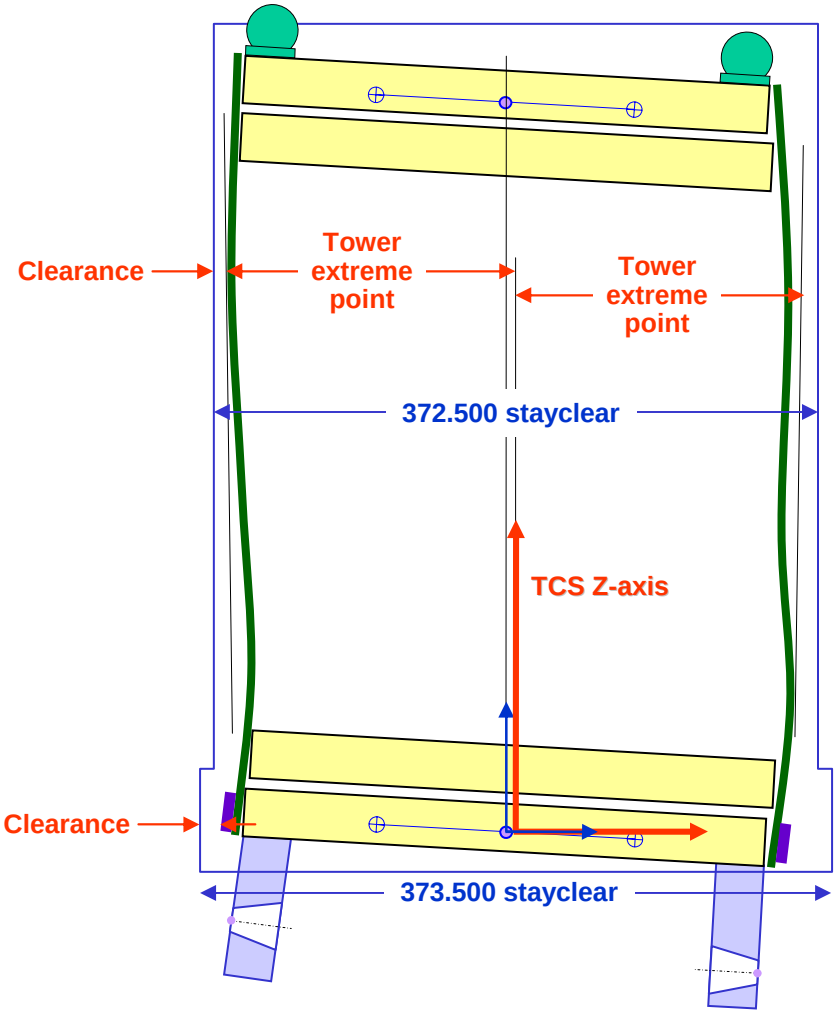
Grid Inspection Conclusions

- All Grid bays have BCS origins and orientations that are acceptable
- TKR modules that are within their stayclears may be integrated into any Grid bay, and will stay within their allowed positions
- The TKR-TKR gap allowance will be preserved with the as-built Grid

- Use the Grid as-is

Tracker Inspection Results

- A Tower Coordinate System (TCS) is defined for each TKR tower
  - This is defined to produce the minimum footprint—or shadow— of the tower
  - The clearance is the difference between the footprint as defined by the tower extreme point and the stayclear
    - Clearance = half-stayclear – extreme point
  - Any clearance > 0 means that the TKR tower is within its stayclear
- Results of inspection of TKR-A through TKR-5
  - Min clearance on sidewall: 0.156
    - This translates to a min clearance at the EMI tape of 0.08
  - Min clearance at washer: 0.078



Tracker Tower Inspection Details

- Sidewall inspection data shows that TKR assembly is done to very tight tolerances
- TKR module dimensions are coming in only slightly larger than nominal
  - This provides for more clearance to the stayclear than expected from the tolerance stack-up

- All delivered TKR modules fit within their stayclears → RFI with no liens
- Keep up the good work

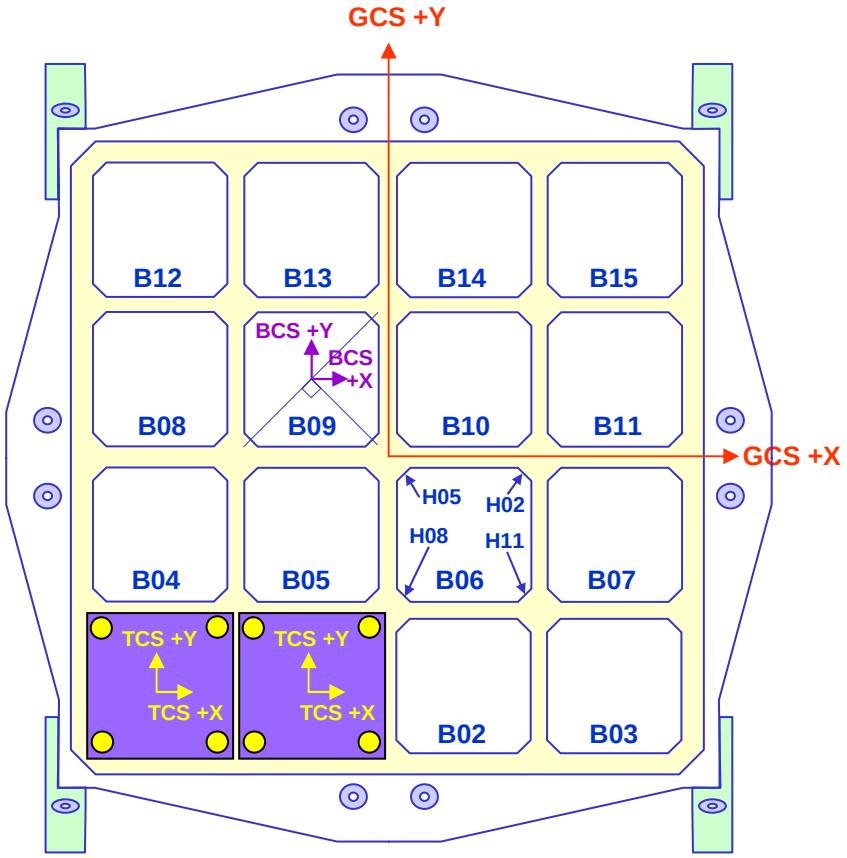
S/N	Sidewall Extreme Point				Bottom Washer Extreme Point			
	+X Wall	+Y Wall	-X Wall	-Y Wall	+X Washer	+Y Washer	-X Washer	-Y Washer
TKR-A	**186.028**	186.029	-186.041	-185.953	186.583	**186.672**	**-186.568**	-186.495
TKR-B	186.000	186.020	**-186.094**	**-186.004**	**186.641**	186.457	-186.531	-186.495
TKR-1	185.963	**186.091**	-186.001	-185.977	186.453	186.492	-186.408	**-186.502**
TKR-2	185.923	185.904	-186.008	-185.892	186.456	186.398	-186.430	-186.499
TKR-3	185.939	185.967	-185.937	-185.984	186.443	186.602	-186.356	-186.407
TKR-4	185.962	186.074	-185.955	-185.966	186.465	186.471	-186.419	-186.341
TKR-5	185.910	186.038	-186.076	-185.962	186.398	186.440	-186.446	-186.466
Average	185.961	186.018	-186.016	-185.963	186.491	186.505	-186.451	-186.458
St Dev	0.042	0.064	0.059	0.035	0.087	0.097	0.074	0.062
Extreme	186.028	186.091	-186.094	-186.004	186.641	186.672	-186.568	-186.502
Clear	0.222	0.159	**0.156**	0.246	0.109	**0.078**	0.182	0.248
Nom	185.875	185.875	-185.875	-185.875	186.530	186.530	-186.530	-186.530
Stayclear	186.250	186.250	-186.250	-186.250	186.750	186.750	-186.750	-186.750

Source: "TKRTowerSurveyDataR3--2005-06-23.xls"

Compiled from TKR End Item Data Package data

LAT Survey Data Processing

- The third step is to integrate the TKR on the Grid, and survey the as-installed location
  - Here, we could use shims to check for a minimum gap between neighboring modules
  - However, this provides little insight into the nature of a problem, since the source of a problem would be a combination of multiple tolerances from two towers and Grid bays
- The actual geometry of both the TKR and Grid are complex, so we stay with evaluating the location of the TKR stayclear to simplify the data processing (this is conservative)
- Steps in post-processing TKR survey data on the LAT
  - From TKR EIDP, pull TKR retro-reflector ball locations on the top of the TKR, with respect to the TKR TCS
  - From LAT survey data, pull TKR retro-reflector ball locations with respect to the LAT GCS
  - With these two sets of related information, the Metrology group finds the translational and rotational offsets of the TKR TCS with respect to the LAT GCS



LAT Top View

LAT Survey Results

- **Any translation or tipping of the TKR TCS from its nominal location means that the half-gap to neighboring modules is closing on one side and opening on the other**
  - **Translations of the TCS directly impact the half-gap width**
  - **Rotations of the TCS produce:**
    - **Tipping: this significantly impacts the half-gap at the top, since the tower is taller than it is wide**
    - **Twisting: this produces additional translation at the tower corners**
- **The combination of the effects of translation and tipping of the TCS are then compared with the allowables (from table on page 4)**

	Allowed	Measured Max
– Motion of TKR stayclear at top of module:	0.635	0.609
– Motion of TKR stayclear at washers near bottom:	0.288	0.239

- **Processed survey data, below, shows that the offsets of the installed TCS' produce tower motions that are within their allowables**

"Tmax", "Bmax" are max allowed offsets of TCS at top and bottom of TKR with TKR still inside its stayclear

Tmax *0.635* Ht 642.6

Bmax *0.288* Wd 186.25

				Evaluation of TCS Location and Attitude on the Grid as Related to the Fit of the TKR Within Its Stayclear								
Bay	Deltas (Act-Nom)						Eval of Top Max Offset/Tip/Twist		Eval of Bot Max Offset/Twist			
	dX	dY	dZ	Xtip	Ytip	Twist	max|dX+Xtip+/-Twist|	max|dY+Ytip+/-Twist|	max|dX+/-Twist|	max|dY+/-Twist|	Top Eval	Bot Eval
B00	-0.089	-0.100	-0.027	-0.410	0.289	0.077	0.576	0.266	0.165	0.177	PASS	PASS
B01	-0.038	-0.027	-0.326	0.031	-0.101	0.047	0.053	0.175	0.084	0.074	PASS	PASS
B02												
B03												
B04	0.011	0.002	-0.182	-0.269	0.071	0.059	0.318	0.133	0.070	0.061	PASS	PASS
B05	-0.108	-0.105	-0.261	-0.129	-0.011	-0.002	0.239	0.118	0.110	0.107	PASS	PASS
B06												
B07												
B08	-0.133	-0.078	-0.071	-0.473	0.276	0.003	**0.609**	0.200	0.136	0.081	PASS	PASS
B09	-0.160	-0.201	-0.153	0.036	-0.063	0.038	0.162	0.301	0.198	**0.239**	PASS	PASS

Source: "TKRTowerSurveyDataR3--2005-06-23.xls"

LAT Survey Details

- This analysis is simplified and conservative
  - Evaluations are based on the TKR stayclears, not the actual hardware
    - The degree to which the hardware is within the stayclear constitutes added margin
  - Evaluations were to the half-gap, meaning that each TKR module TCS must be placed within its allowed location on the Grid, independent of the neighboring modules
    - Any systematic pattern of Grid hole location errors constitutes added margin
    - If neighboring modules are offset away from a module, the gap will be larger than this worst-case estimate
- Conclusions:
  - TKR modules are being positioned accurately and within their allowed tolerances
  - The residual TKR-TKR gap is large enough to ensure no collision during testing and launch

Take-Away 1: Survey Repeatability

- **TKR modules in Bays 0 and 4 have been surveyed 4 times in different load configurations:**
  - **Srv1 (11-Apr-2005): Grid Horizontal / Two Towers**
  - **Srv2 (12-Apr-2005): Grid Vertical / Two Towers**
  - **Srv3 (15-Apr-2005): Grid Horizontal / Two Towers Plus 14 Bay Weights**
  - **Srv4 (13-Jun-2005): Grid Horizontal / Six Towers Plus 10 Bay Weights**
- **Translation**
  - **0.037 mm X/Y 1-sigma error is consistent with precision of optical survey method**
  - **Z-error (1-sigma = 0.073 mm) is expected to be worse, given the flat survey angles**
- **Rotation**
  - **Top offset errors are larger than translation → this eliminates margin on gap**
  - **This is expected from the survey method, but there may be a small component of sag…**

Comparison of Survey-to-Survey Spread of Data

Bay	TCS Actual Surveyed Coord's (mm, rad)						Deltas (TCS Act-Nom)			Offsets at Top			Survey Info	
	X	Y	Z	RX	RY	RZ	dX	dY	dZ	Xtip	Ytip	Twist	ID	Date
B00	-561.772	-561.754	261.611	-0.000318	-0.000720	0.000420	-0.022	-0.004	0.148	-0.463	0.204	0.078	Srv1	11-Apr-05
B00	-561.834	-561.803	261.542	-0.000490	-0.000455	0.000410	-0.084	-0.053	0.080	-0.292	0.315	0.076	Srv2	12-Apr-05
B00	-561.790	-561.782	261.504	-0.000293	-0.000801	0.000415	-0.040	-0.032	0.041	-0.515	0.188	0.077	Srv3	15-Apr-05
B00	-561.839	-561.850	261.435	-0.000449	-0.000639	0.000413	-0.089	-0.100	-0.027	-0.410	0.289	0.077	Srv4	13-Jun-05
Average:	-561.809	-561.797	261.523	-0.000388	-0.000654	0.000414	-0.059	-0.047	0.061	-0.420	0.249	0.077		
St'd Dev:	0.033	**0.040**	0.073	0.000097	**0.000148**	0.000004	0.033	0.040	0.073	0.095	0.062	0.001		

Bay	TCS Actual Surveyed Coord's (mm, rad)						Deltas (Act-Nom)						Survey Info	
	X	Y	Z	RX	RY	RZ	dX	dY	dZ	Xtip	Ytip	Twist	ID	Date
B04	-561.732	-187.179	261.396	0.000105	-0.000369	0.000350	0.018	0.071	-0.066	-0.237	-0.067	0.065	Srv1	11-Apr-05
B04	-561.743	-187.217	261.380	-0.000041	-0.000198	0.000342	0.007	0.033	-0.082	-0.128	0.027	0.064	Srv2	12-Apr-05
B04	-561.713	-187.209	261.293	0.000031	-0.000487	0.000330	0.037	0.041	-0.169	-0.313	-0.020	0.062	Srv3	15-Apr-05
B04	-561.739	-187.248	261.280	-0.000111	-0.000419	0.000318	0.011	0.002	-0.182	-0.269	0.071	0.059	Srv4	13-Jun-05
Average:	-561.732	-187.213	261.337	-0.000004	-0.000368	0.000335	0.018	0.037	-0.125	-0.237	0.003	0.062		
St'd Dev:	0.013	0.028	0.059	0.000093	0.000123	0.000014	0.013	0.028	0.059	0.079	0.060	0.003		

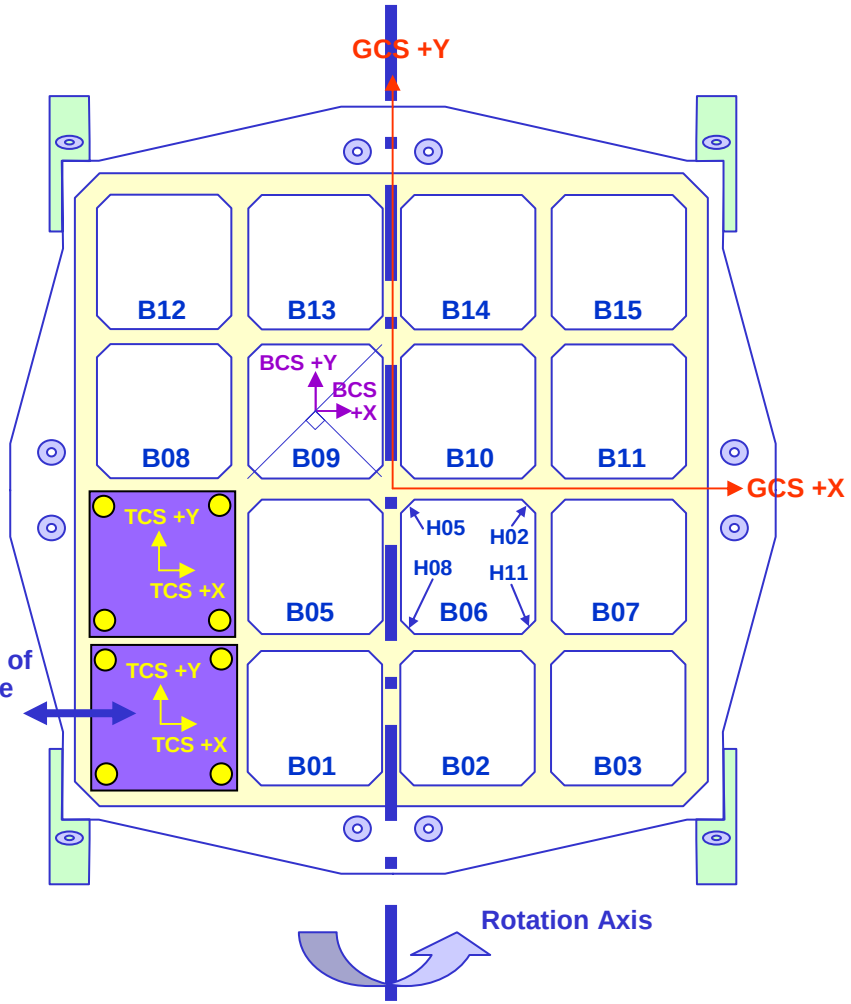
Take-Away 2: Grid Sag

- Predicted swing of the top of a TKR due to the sag of the Grid is 0.245 mm at MECO (6.8 g static-equivalent acceleration)
- This is equivalent to 0.036 mm due to gravity loading (when held at the SC mounts)
- Survey results suggest that there is a ~0.150 mm differential tip from horizontal to vertical for bays 0 and 4
- However, there should also be an increase in tip between the first survey with an empty Grid, and the third and fourth, with full LAT weight, and there does not appear to be
- This is worth tracking in future surveys

Bay	Deltas (TCS Act-Nom)			Offsets at Top		
	dX	dY	dZ	Xtip	Ytip	Twist
B00	-0.022	-0.004	0.148	-0.463	0.204	0.078
B00	-0.084	-0.053	0.080	-0.292	0.315	0.076
B00	-0.040	-0.032	0.041	-0.515	0.188	0.077
B00	-0.089	-0.100	-0.027	-0.410	0.289	0.077
Average:	-0.059	-0.047	0.061	-0.420	0.249	0.077
St'd Dev:	0.033	0.040	0.073	0.095	0.062	0.001

Bay	Deltas (Act-Nom)					
	dX	dY	dZ	Xtip	Ytip	Twist
B04	0.018	0.071	-0.066	-0.237	-0.067	0.065
B04	0.007	0.033	-0.082	-0.128	0.027	0.064
B04	0.037	0.041	-0.169	-0.313	-0.020	0.062
B04	0.011	0.002	-0.182	-0.269	0.071	0.059
Average:	0.018	0.037	-0.125	-0.237	0.003	0.062
St'd Dev:	0.013	0.028	0.059	0.079	0.060	0.003

Expected motion of tops of TKR's due to gravity is in X-direction



LAT Top View

Take-Away 3: TCS-to-BCS Alignment

- From the Grid survey, we had constructed Bay Coordinate Systems (BCS) for each of the 16 Grid bays, using the actual locations of the TKR interface holes
- From the TKR inspection, the Tower Coordinate System (TCS) was built to center the actual TKR module in a perfect bay

- Ideally, if an actual tower is integrated into the as-built Grid, the TCS should align perfectly to the BCS
  - The degree to which they do NOT align gives an indication of how accurately we are aligning the towers as they go into the Grid
  - Our tolerance budget for this was 0.015 mm, given some single-cone-set tests in Pisa
- Survey numbers below show that towers are being integrated to much worse accuracy than what we budgeted
  - Alignment accuracy of the TCS averages around 0.200 mm
  - In some cases, the offset to the BCS is larger than the tower's offset to its nominal location
  - This explains why the half-gap clearance is relatively small, given that tower dimensions are coming in near their nominal size
- Options
  - Check this accuracy in Pisa by comparing tower inspection with tower + base plate inspection
  - Double-check cone-set alignment at SLAC prior to integrating a TKR tower on the LAT

Bay	Deltas (Act-Nom)			Delta (TCS-BCS)		
	dX	dY	dZ	dX	dY	dZ
B00	-0.089	-0.100	-0.027	-0.195	-0.215	-0.053
B01	-0.038	-0.027	-0.326	-0.162	-0.097	-0.328
B02						
B03						
B04	0.011	0.002	-0.182	-0.026	-0.045	-0.207
B05	-0.108	-0.105	-0.261	-0.115	-0.126	-0.229
B06						
B07						
B08	-0.133	-0.078	-0.071	-0.241	-0.112	-0.103
B09	-0.160	-0.201	-0.153	-0.224	-0.224	-0.180

Summary

- TKR module surveying of the first six modules has produced good initial results
  - The survey data is useable, with errors in the range of what was expected
  - The surveys shows that all TKR modules are within their stayclears, and are placed within allowed tolerances on the Grid
  - The gaps between neighboring modules hass in all cases been preserved
- Areas for further investigation
  - TKR: look into module alignment at Pisa and/or double-check cone-set alignment at SLAC to try to reduce larger-than-expected alignment errors
  - Look into adding two more surveys
    - Add a survey after 10 towers to better track interim results—especially if changes are made to TKR alignment in Pisa or in I&T
    - Add a Grid-vertical survey after all 16 towers are complete for a direct comparison of horizontal-to-vertical to better gauge gravity-induce sag