LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Advanced LIGO Quad Suspension Assembly Procedure

Mark Barton, Betsy Bland, Jodi Fauver, Joe O'Dell, Brett Shapiro and Ian Wilmut.

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California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

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1 Introduction

1.1 Purpose and Scope

This document describes the assembly procedure for the production version of the quad suspension, from receiving of parts through to a balanced and aligned all-metal build in storage.

Mark Barton and Betsy Bland wrote most of the final version, flagrantly recycling from documents by Joe O'Dell, Brett Shapiro and Ian Wilmut.

Version -v1 is still very much a work in progress but is being released to the DCC for wider commenting.

1.2 References

T080108-00: Notes on Lower Quad Installation at LASTI.
T080165-00: Metal Quad Noise Prototype Balancing and Alignment Procedure.
T060040-v1: Noise prototype Assembly procedure.
G070359-00: LASTI Tooling (instructional DVD)
E070292-00, H. Armandula, Optics Cleaning Specification - First Contact™
E960022-v4: LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures
T040108-03: Blade, wire and clamp process specification

Top level assembly:
D0901346-v2: Advanced LIGO Quadruple Suspension
E0900316: ALIGO QUAD DRAWING TREE
E0900167: Bill of Materials for the ETM / ITM Quad Suspension Assembly (Production)
T0900590: Quad production status

Subassembly drawings:
D060310: QUAD N-PTYPE TABLECLOTH, Tablecloth (Noise Prototype)
D060324: Quad N-Ptype Top Stage, BLADE CARTRIDGE
D060341: QUAD N-PTYPE, PENULTIMATE REACTION MASS, ETM CONFIGURATION
D060355: Quad N-Ptype, Dummy Test Mass Assembly Tooling
D0902075: Quad N-Ptype, DUMMY PENULTIMATE MASS
D060356: Quad N-Ptype, Dummy Test Reaction Mass Assembly Tooling
D060375: Quad N-Ptype, UI MASS
D0902233: QUAD UI MASS REACTION CHAIN
D060403: Quad N-Ptype Top Mass, TOP MASS - MAIN CHAIN
D0902031: Quad N-Ptype Top Mass - REACTION CHAIN
D060454: QUAD N-PTYPE LOWER STRUCTURE, INNER LOWER STRUCTURE, SUSPENSION STRUCTURE
D060492: Quad ETM/ITM, Upper Structure Weldment
D070056: Quad N-PType, Quad Dog Clamp
D070214: Quad N-PType Wiring Harness, Top Ring Wire Clamp
D070217: Quad N-PType Wiring Harness, Upper Structure Stay Wire Clamp
D070538: Quad ITM/ETM, Implementation Ring Test Chain

D070539: Quad ITM/ETM, Implementation Ring Reaction Chain
D070552: ITM/ETM Structure, ITM/ETM Sleeve
D080241: Earthquake Stop Assembly
D090433: THIS, TRANSPORT PADS, QUAD SUS
D090434: THIS, FRONT TRANSPORT PAD, QUAD SUS
D0901342: SLEEVE - LS - WEDGE 1
D0901343: SLEEVE - LS - WEDGE 2

D060516: Wire jig assembly drawing (with usage diagrams)
D0902643: Top Wire Clamp Wire Assembly
D0902644: Middle Clamp Wire Clamp Assembly
D0902645: Bottom/Final Clamp Wire Clamp Assembly

Holo-Krome Bolt Torque Data Sheet (http://www.holo-krome.com/pdf/techbk34-40.pdf): recommended bolt torque values from Holo-Krome.
T080230-v1: Quad Pendulum Structure Pushers
EXXXXXX - Inventory Control Manual
F0900XX – Inventory Control Import Template
E0900047: aLIGO Contamination Control Plan

1.3 Version history

1/14/10: First pre-v1 draft, adapting T060040-v1

1/18/10: Second pre-v1 draft adding stuff from Brett's T080165-00.

2/24/10: Third-pre-v1 draft with input from Betsy on ICS, receiving, cleaning/baking, making of clamp-wire-clamp assemblies, etc.

2/26/10: v1. Tidying up by Mark B. Still very much a work in progress but released for comment.

2 Template

Copy and paste this to get another instance of the nice tables. Be sure to select the blank line after the table or funny things may happen (tables merging, etc). After adding a table, check the numbering of the table you added and the one below it - the setting to restart the numbering at 1 may have been cleared for either or both. If this is not what you want, click in the first numbered cell, choose Format->Bullets and Numbering… and click the “Restart numbering” radio button.

Step	What	Where	Time	People	Tools
1					

3 Preparation

Advanced LIGO has implemented a new Inventory Control System (ICS) which is designed to record all aLIGO hardware as it moves through receiving, inspection, clean, bake, storage, shipment, and assembly processes. The ICS is meant to replace the shipping type paper traveler used in iLIGO. While the ICS is still in final development of Assembly and Test records as of this writing, the hope is that the engineering teams will be able to utilize ICS to record all aspects of the lifetime of a part from its initial receipt through to measurements taken during commissioning and installation. The sites have dedicated staff to help with managing the data related to the processing of parts in ICS. Engineering staff should become familiar with the ICS such that they can utilize it for their own record keeping and data management. If the ICS fails to facilitate data that you need to record, process travelers (PT) can be placed on the DCC. In either case, make sure to record all serial numbers and data in the ICS or the DCC during the following steps.

3.1 Receiving/inventory

3.1.1 Receiving/inventory of metal parts

Upon receipt of shipments of SUS parts, the following steps should be performed:

Basic inspection of shipment by receiver (crate damage, etc). Packing slips should be sent (hardcopy or emailed) to Jennie Murdock at LHO. Person performing this step should notify site subassembly lead of the shipment arrival.

Inventory Control and inspection performed by ICS person and site subsystem lead as parts are unpacked. Drawing numbers, serial numbers, and quantities will be imported into the ICS database via spreadsheet templates (F0900052). This is a good time for QA/QC and engineering inspections. The following processes can now be recorded in ICS by grouping the parts into Loads.

Parts get separated into cleaning loads based on their level of cleanliness, and moved to the appropriate cleaning station.

Parts get separated into clean and bake loads based on their material – see E960022. Sorting should be reflected in the Load records in ICS, where instructions to technicians can be added for any special handling or material considerations.

Parts get processed as per E960022.

Parts get stored in clean storage areas until assembly.

3.1.2 Receiving/inventory of glass parts

[?? Different from metal?]

3.2 Cleaning/Baking

Process all parts except for the Dummy Masses as Class A per E960022. Dummy Mass D0603XX is to be processed as Class B, as it will later be swapped out with Class A glass mass. All Parts should be processed as Class A or B prior to Helicoil installation.

3.3 Helicoils

Install all the helicoils in all the parts and make sure they are free running and not cross threaded, remove the tangs. Perform Helicoil inspections as per XXXXXXX.

4 Subassemblies

Assign each subassembly with a unique serial number based on the parent number which can be used for referencing data taken on that subassembly. For example, if 3 Top Mass Assemblies are assembled from drawing number D060421, the units should be assigned serial numbers like:

D060421-001

D060421-002

D060421-003, and so on. As individual parts are added to the subassembly, record their serial numbers as part of that subassembly. The overall subassembly number (i.e. D060421-001) can now be used in the ICS to track further operations performed on that subassembly. These subassemblies will eventually become associated with their parent QUAD which will have its own serial number, such as D0901648-001 (aka QUAD 001). Label the bag with the newly designated subassembly and serial number after wrapping and bagging.

When weighing subassemblies, use the high precision scale dedicated for the SUS assemblies.

4.1 Dummy test mass (D060355)

Prior to assembly, this mass (D060358) can be processed as CLASS B, as it will be swapped with a glass mass. Assemble all masses as per their assembly drawings. Assemble each mass with the addable masses such that each has the appropriate weight.

4.2 Dummy main chain penultimate mass (D0902075)

Prior to assembly, this mass (D060358) can be processed as CLASS B, as it will be swapped with a glass mass. Assemble all masses as per their assembly drawings. Assemble each mass with the addable masses such that each has the appropriate weight.

4.3 Dummy CP or ERM (D060356)

ERM stands for End Reaction Mass (chosen to avoid confusion with Recycling Mirror), which is also known as Re Test Mass. Note that due to abandonment of a plan to have an ERM of heavy glass, the production dummy ERMs are identical to the dummy CPs and lighter (approximately 22 kg) than the dummy ERM used in the all-metal build of the LASTI prototype (approximately 40 kg).

Prior to assembly, this mass (D060357) can be processed as CLASS B, as it will be swapped with a glass mass. Assemble all masses as per their assembly drawings. Assemble each mass with the addable masses such that each has the appropriate weight.

4.4 Penultimate Reaction Mass for CP or ERM (D060341)

This mass is also known as Pen Re. Just as all CPs and ERMs are now identical (see note in previous section), so are all the penultimate reaction masses. This mass needs to be cleaned to CLASS A because it is not a dummy and will be installed in vacuum.

4.5 Ring heater

ITM configuration only.

4.6 Wire assemblies

Follow the procedure in Section 4.10 for each assembly, taking account of the general notes immediately below, and the per-assembly-type notes in Sections 4.7 through 4.9.

Pay attention to the exploded views in the D060516 wire assy drawings – these show when to use what grooves in the jaws.

Take care to not over stress or bend the wires when releasing the wire sets from the jig. Also take care when storing. Wire sets should be stored in dry storage along with the spools of wire.

When setting up the wire in the jig, note that it should never bend around any fixture pieces except for at the clamp and the tuners. If the wire bends around any of the fixture, then recheck the fixture setup.

4.7 Top wires (D0902643)

There are 2 grooves in the D060334 jaws, but only one groove will be used for the Top Wire assembly. Use ~1" segments of wire inserted into the empty wire groove in each clamp.

Use the groove that is more centrally located in the wire clamp assembly to mount the wire. Use the outer groove for the "dummy" wire.

4.8 Middle wires (D0902644)

Note in the drawings which grooves to use in the clamps of this assembly. Some are used, some are not.

4.9 Bottom/Final wires (D0902645)

This is a compound assembly which includes the UIM-PM wires and the loop supporting the TM/CP/ERM.

4.10 General clamp-wire-clamp assembly procedure

Step	**What**	**Where**	**Time**	**People**	**Tools**

Step	What	Where	Time	People	Tools
2	Class B the wire jig assembly. Helicoil the assembly.	VPW	2 days	1	
3	Using the Wire Jig assembly drawings as a guide, set up the jig fixture for the wire segment you will be assembling. There are 4 segments of wire assemblies to assemble for every QUAD. The jig can be reconfigured for each of these segment lengths. Note: Use gauge blocks of the thickness listed on the assembly drawings to set the jig fixture pieces the appropriate distance apart, and square relative to each other.	Lab	20 min.		
4	Cut a length of wire long enough to span the section of the jig you will be using.				
5	Clean the wire by wiping it thoroughly with acetone many times, followed by a thorough wipe with methanol. Take care to not bend or "kink" the wire during any of the subsequent handling steps. [?? Check]		5 min.	1	
6	Clamp the wire into the clamps held by the fixture, taking care to secure the free ends tightly in the outer fixture jaws and the guitar tuner.				
7	Snug up the "real" wire clamps such that the wire is free to slide through them, but does not chatter when the wire is strummed during the following tuning steps.		10 min	1	
8	Setup an oscilloscope (such as Tektronix TDS 2012B) to trigger on the peak of the frequency specified in the assembly drawings for the segment you are working on.		15 min	1	
9	Set cursors at +/-2Hz from the specified frequency.				
10	Hook the guitar pickup BNC to the scope.				
11	Place the guitar pickup on the jig just under the wire such that it will pickup the sound of a strum.				
12	Strum the wire like you would on a guitar, to see the frequency peak on the scope. Tension the wire by turning the guitar tuner until the peak is centered between the cursors on the scope.				
13	Tighten the QUAD wire clamps and check that the frequency peak has not moved out of the cursor range. If it has, loosen the clamps slightly		10 min	1	

Step	What	Where	Time	People	Tools
	and retune by adjusting the tension. This might take a few iterations.				
14	Remove wire from jig by first loosening the guitar tuners, and the fixture jaws. Take care not to induce any stretching in the wire segment when removing it from the fixture.				
15	Repeat wire assembly steps above for each segment length necessary for the full QUAD assembly.				
16	Assign each wire assembly a unique serial number and record final resonance frequencies for each in the ICS/PT.				
17	Store as CLASS A in dry storage until ready for installation into a full QUAD Assy		10 min.	1	

4.11 OSEMs

Assemble AOSEMs as per E090XXX. BOSEMs should be delivered by Birmingham, fully assembled and ready for Class A use.

4.12 Top mass

In general, the more carefully each assembly and alignment step is done, the easier later steps will become. For example, the more accurately the blade springs were installed during assembly, the easier it will be to balance pitch.

Step	What	Where	Time	People	Tools
18	Insert helicoil repair in all D060430 top plates. (Not in picture book.)				Standard Class B Tool Kit
19	Choose blades which are a matched pair. TBW. Each set of blades also corresponds to a particular blade clamp D0604XXX				
20	Assemble one Top Mass and one Reaction Top Mass as per the picture book D0900XX, until page XX.			2	Weight set for blade straightening
21	Perform the Creep Air Bake on the partial assy at 120 deg C for 1 week,		1 week		

Step	What	Where	Time	People	Tools
	as per T0900XXX.				
22	Choose OSEMs which are matched to TBD.				
23	Complete assembly of the Top Mass and Reaction Top Mass as per the picture book. Notes: Take care when pressing the steel disks into the aluminum ECD and flag holders, as the aluminum can be easily bent. Handle magnets carefully as they are very strong and some are brittle. As well, be careful with tools in proximity to the magnets as many tools in the kits are magnetic. Torque all fasteners as per TBW.			2	Clean Press Standard Class B Tool Kit
24	Addable Mass should be added symmetrically onto the assembly until the unit weighs the specified weight, as per TBW.				
25	Store the sub assemblies until you are ready to install them into a QUAD. Note: Magnets should be removed from assembly and stored with the unit separately.				

4.13 UI Mass

In general, the more carefully each assembly and alignment step is done, the easier later steps will become. For example, the more accurately the blade springs were installed during assembly, the easier it will be to balance pitch.

Step	What	Where	Time	People	Tools
26	Choose blades which are a matched pair. TBW. Each set of blades also				

Step	What	Where	Time	People	Tools
	corresponds to a particular blade clamp D0604XXX				
27	Assemble one UIM and one Reaction UIM as per the picture book D0900XX, until page XX.			2	Weight set for blade straightening
28	Perform the Creep Air Bake on the partial assy at 120 deg C for 1 week, as per T0900XXX.		1 week		
29	Choose OSEMs which are matched to TBD.				
30	Complete assembly of the Top Mass and Reaction Top Mass as per the picture book. Notes: Take care when pressing the steel disks into the aluminum ECD and flag holders, as the aluminum can be easily bent. Handle magnets carefully as they are very strong and some are brittle. As well, be careful with tools in proximity to the magnets as many tools in the kits are magnetic. Torque all fasteners as per TBW.			2	Clean Press Standard Class B Tool Kit
31	Addable Mass should be added symmetrically onto the assembly until the unit weighs the specified weight, as per TBW.				
32	Store the sub assemblies until you are ready to install them into a QUAD. Note: Magnets should be removed from assembly and stored with the unit separately.				

4.14 Upper structure

In general, the more carefully each assembly and alignment step is done, the easier later steps will become. For example, the more accurately the blade springs were installed during assembly, the easier it will be to balance pitch.

4.15 Lower structure

4.16 Blades

The blades have had an initial creep bake as detailed in T040108-03 [?? Is this the latest?] and have then been matched in stiffness (equal deflection under a constant load), and have similar (within 5mm) deflected shapes.

[?? Does this belong here?] Ensure all the blade clamps have been correctly angled to allow for blade stiffness.

4.17 Sleeve

Ensure by trial fit that the upper and lower structure correctly interface to the sleeve.

5 Glass prep

5.1 Test mass

5.1.1 Test mass ear bonding

[?? describe ear bonding]

5.2 Penultimate mass

5.2.1 PM ear bonding

[?? describe ear bonding]

5.3 PM prism gluing

[?? describe prism gluing]

5.4 CP

ITM configuration only.

5.4.1 CP prism gluing

[?? describe prism gluing]

5.4.2 CP electrical connections

Step	What	Where	Time	People	Tools
1	Check the electrical continuity of the ESD cables. (The cables are *extremely* prone to failure at the end where the gold connectors have been crimped on.)		1 day for all steps		ohmmeter
2	Take the CP out of its case, remove the face-plate from the ESD side, and lay it with the ESD side up in a clean room. [It was very difficult to remove the face plates because they were quite tight and there were no vent grooves in them.]				
3	Carefully wipe the face and sides of the optic with lint-free wipes moistened with methanol [acetone?] to remove dust and dirt.				methanol [??acetone], wipes
4	Cut gold tabs to appropriate size: width about the same as the traces in the ESD mask, length sufficient to protrude about 5 mm off the edge of the optic. (This will be different for different traces.) [Brett: 5 mm turned out to be too much given the narrow clearance between the CP and the structure – it should be more like 2-3 mm.)				tabs
5	Crimp a furrow across the end of the gold tab which will be used to support the coax cable at a later step.				pliers
6	Set up a bottle of clean, dry nitrogen with a regulator and nozzles to direct a flow of nitrogen across the work area.				N2 bottle, regulator, nozzles

Step	What	Where	Time	People	Tools
7	Repeat the next few steps for each tab to be soldered:				
8	Point the nozzles at the end of the ESD trace that the tab is to be attached to.				
9	Place a small bead of indium on the end of the trace, lay the flat end of the tab on top and cover with an aluminium button.				indium solder, Al button
10	Press a soldering iron heated to 600 degrees F onto the button and keep it there until 10 seconds after the indium melts. The button will visibly sag when the solder melts. Remove the button and inspect the joint. Too much heat can damage the pattern, so do not keep the iron there longer than necessary.				soldering iron, button
11	Remove a length of shield approximately 1.5" long from the end of the coax, exposing the (very delicate) central conductor and inner insulation.				wire stripper
12	Carefully strip the inner insulation exposing 2 to 3 mm of the central conductor.				wire stripper
13	Lay the end of the intact section of shield into the groove in the tab and roll the end of the tab over so that the shield is gripped.				pliers
14	Carefully bend the inner conductor around towards the body of the tab and solder it there, using the same procedure as for the tab. Maintain slight pressure on the tab at all times so that it does not move if it the solder behind it should melt.				soldering iron, solder, button
15	Test the electrical continuity from the pattern to the end of the cable.				ohmmeter

5.5 ERM

5.5.1 ERM prism gluing

[?? describe prism gluing]

5.5.2 ERM electrical connections

As for CP.

6 Main assembly

Step	What	Where	Time	People	Tools
1	Download the quad traveler template, E0900371 (a Microsoft Excel spreadsheet), start a new copy under a new DCC number and title as described in the instructions sheet of the template.				
2	Record the new traveler DCC number in the Related Documents field of E0900371 [?? and in the inventory control system in the record for the suspension being assembled].				
3	In the steps below, record the called-for data in the traveler spreadsheet. After each work session, resubmit the updated traveler to the DCC as a new version.				

6.1 Top stage

Step	What	Where	Time	People	Tools
4	Install empty upper structure on the gazebo, attach with at least 16 dog clamps (4 per side, with 2 per corner).				
5	Install all four top stage blade units in place. Check the tips are central, and the location holes align.				
6	Ensure all blade tips are held well down with blade stops. Target is that the tips are 2mm below nominal (108mm from the optic table to the blade top).				

6.2 Tablecloth and top mass

Step	What	Where	Time	People	Tools

Step	What	Where	Time	People	Tools
7	Lie two 36mm cross bars across the lower structure bottom ring and rest the two top masses approximately in place (the upper structure removable braces work well)				
8	Assemble the tablecloth side plates in place with no OSEMs/ECD assemblies. Install all the dowels to locate it nominally WRT to the structure.				
9	With the stops raise the top masses into place . Position nominally in x and y using dowels and approximately 10mm too high in z (do this by inserting the stops too far).				
10	Connect the top two masses to the top stage, bolting the top wire clamps to the top blade tips and the top mass. The top plate of the top masses can be removed to make this easier.				
11	Lower top two masses to nominal position - note the top stage blade tips may need to be pushed down for this.				

6.3 Lower structure

6.3.1 LSAT

Step	What	Where	Time	People	Tools
12	Assemble both halves of the lower structure assembly tooling side by side on either the floor or a low table. Note when viewed from above they should look something like: ⊓ ⊔ ideally with the rear of the penultimate mass easily accessible.				
13	Install the respective halves of the lower structure into the tooling.				

6.3.2 Reaction chain

Note the test and reaction chains are subtly different approaches, either is acceptable, the only reason they are different is that they are more-representative of the glass procedure.

Step	What	Where	Time	People	Tools
14	Add the reaction UI mass into place on fully retracted vertical stops, this puts the masses 10mm below nominal (nominal is UIM base plate bottom 70.2mm from lower structure cross member top).Note: OSEMS should be in place.				
15	Add the Penultimate reaction mass in to a position in its nominal position WRT lower structure (on fixed PFA440HP pads); set roll (approximately) Note: OSEMS should be present and in the approximately correct position.				
16	Add the reaction test mass ~3mm above nominal (use #1 spacers); approximately set roll by eye.				
17	Add the UIM-PenRe-TestRe wire assemblies to both sides. Roll test mass and Pen mass as required.				
18	Lower test reaction mass to its nominal position (use #2 spacers) note the mass will initially have to be lifted to remove the #1 spacers				
19	Raise the UI mass to its nominal position on the vertical stops taking care to keep it horizontal.				
20	Raise the UI mass further to lift the PenRe mass and remove the PFA440HP pads below the PenRe mass. Lower the UI mass to get the PenRe mass back into its original position.				
21	Remove the stops from below the test mass to ensure everything hangs stabaly and with no gross pitch.				
22	Lock all three masses in their nominal positions (leaving the wires all in tension).				

6.3.3 Main chain

Step	What	Where	Time	People	Tools
23	Add the test UI mass into place on partially retracted vertical stops 10mm below nominal.				
24	Add the Penultimate test mass in its nominal position WRT lower structure with magnets omitted (on fixed PFA440HP pads); set roll by eye.				
25	Add the test mass 3mm (using #1 spacer) above nominal.				
26	Approximately set the roll.				
27	Add the UIM-Pen-Test wire assemblies and attach to all 3 masses, note the UIM blade tips may need to be worked up and down for this.				
28	Raise the UI mass to its nominal position on the vertical stops taking care to keep it horizontal.				
29	Lower and release the test mass from all its stops.				
30	Lower and release the test mass from all its stops.				
31	Slightly raise the UIM mass allowing the penultimate mass to raise and remove its PFA440HP pads (upper stops need to be retracted). Note, at this point all masses should be suspended for the first time so care should be taken that no unexpected pitches occur although it is quite unlikely. Lower the UIM to its nominal along with penultimate mass suspending it.				
32	All masses can now be locked in place. The simplest thing to do is to lock them in their nominal positions. A more representative thing to do is to raise the test mass 8mm as it will be when there is glass. For now nominal positions is recommended.				

6.4 Using the triple-hang tooling

Step	What	Where	Time	People	Tools

Step	What	Where	Time	People	Tools
33	Start with main or reaction chain lower structure with all masses and wires in place, with the UIM approximately 4 mm high of nominal on its stops, and with UIM blades overloaded by 5 mm.				
34	Check UIM is level and if not, adjust earthquake stops till it is.		5 min	2	bubble level
35	Retract upper earthquake stops on bottom mass.		5 min	2	hex keys
36	Screw in lifting screws on lower earthquake stops a tiny amount to ease weight on pad spacers.		2 min	2	hex keys
37	Remove pad spacers.		1 min	2	
38	Retract lifting screws on lower earthquake stops until optic is suspended.		5 min	2	hex keys
39	Check that optic is level relative to structure by eye – debug if not.		1 min++	2	
40	Retract upper earthquake stops on PM.		5 min	2	hex keys
41	Retract overload screws on UIM blades, monitoring lower masses. If blade strength is matched to payload, PM should be about 4 mm off lower stops (same as UIM was high to begin with).		5 min	2	hex keys
42	Place 12 mm slip gauge on top of each UIM blade in turn and adjust blade height until top of slip gauge is level with reference notch in upright of UIM blade stop bridge (D060399).		5 min	2	slip gauge
43	Check that PM is level relative to structure by eye – debug if not.		1 min++	2	
44	On reaction chain, remove pitch adjuster, remove cable clamp, refit pitch adjuster.		10 min	2	hex keys
45	Fit wire assemblies from triple-hang tooling to UIM.		5 min	2	hex keys
46	Fit triple-hang tooling spacer blocks to top of lower structure.		5 min	2	hex keys
47	Fit triple-hang tooling top plate to spacer blocks.		5 min	2	hex keys
48	Connect wire assemblies to blades on triple hang tooling.		5 min	2	hex keys
49	Release overload screws on triple-hang tooling.		2 min	2	hex keys

Step	What	Where	Time	People	Tools
50	Check that all three masses are level relative to structure by eye – debug if not.		1 min++	2	
51	Reapply overload screws on triple-hang tooling until tension is off wire assemblies.		5 min	2	hex keys
52	Disconnect wire assemblies at blades triple-hang tooling.		5 min	2	hex keys
53	Remove triple-hang tooling top plate and spacer blocks.		5 min	2	hex keys
54	Disconnect wire assemblies at UIM.		5 min	2	hex keys
55	On reaction chain, remove pitch adjuster, fit cable clamp, replace pitch adjuster.		10 min	2	hex keys
56	Repeat with other chain.				

6.4.1 Lower structure wrap-up

57	Ensure all 6 masses are in their nominal positions and are secured with stops that are wrench (not finger) tightened.				
58	Use the genie to manipulate the two structures so that they are face to face. This may involve moving one or both of them.				
59	Bolt two halves of the lower structure together, also bolt the two halves of the lower structure assembly tooling together with the connection plates (4 off)				
60	Unlock test and penultimate masses in both chains and verify that the penultimate masses are parallel, and that the test reaction mass is hanging at the correct angle. Also verify that there is no differential yaw in each chain. Correct if required (locking the round masses, releasing the UIM masses and manipulating them is the recommended method).				

6.5 3-in-1 assembly

Step	What	Where	Time	People	Tools
61	Lift lower structure and tooling on to the 5 axis table, ensure that is correctly centred, and that the table will go low enough that the lower structure will fit under the upper, bolt down with dog clamps (8 min).				
62	Wheel trolley and lower structure under upper structure on gazebo.				
63	Raise lower structure as far as it will go (~28mm above nominal), so that the legs of the lower structure pushes up against the upper structure, note the lower structure must be correctly orientated, (test mass on test chain side).				
64	Use the slack in the UI wires to connect to them to the top masses. Note that the top masses are in their nominal positions WRT the upper structure and the UI masses are in their nominal position WRT the lower structure. If necessary lower the blades on top mass using the stops in order to allow the wires to be connected.				
65	Let down the Lower structure into its nominal position, (28mm gap)				
66	Insert implementation shim and connect lower and upper structures, 8 bolts.				

6.6 Suspending

In general, the more carefully each assembly and alignment step is done, the easier later steps will become. For example, the more accurately the blade springs were installed during assembly, the easier it will be to balance pitch. The more precisely pitch is balanced on the first time through the alignment procedure, the fewer iterations will be needed to align all OSEMs, ECDs, and ESD.

While making adjustments on the quad make sure to watch out for touching stops and for interferences between the chains at every step. In particular the top masses have tight clearance around the blade spring clamp bolts. These bolts tend to get caught under the top plate of the opposing top mass if pitch and roll are not carefully aligned. There is nothing worse than spending an hour making adjustments only to discover that it was all for naught because a screw you did not see was touching one of the masses.

Remember that the blade springs magnify the tilts of the masses below them because their compliance allows for differential tilt between the masses.

Pitch is likely to cause a lot of trouble if the blade spring alignment within the rectangular masses is off. Pitch specifically is sensitive to errors in the blade assembly because any lateral misalignment of the blade tips away from the center of mass at each stage will generate a torque that will introduce a differential pitch between that stage and the one above it. If this problem is too extreme, it will be impossible to meet all the constraints of the OSEMs and test masses simultaneously, and the springs will need to be repositioned. Each blade tip should have exactly 5 mm of clearance on either side. Intolerable errors are on the order of a few tenths of a mm. More details on the spring positioning are in the procedure below.

Step	What	Where	Time	People	Tools
67	Ensure reaction top mass is horizontal and in its correct position.				
68	Release test reaction mass and then pen re mass, check the blade tips are still at the correct height in the UI reaction mass and then release the UI reaction mass.				
69	Release test mass and then pen test mass, check the blade tips are still at the correct height in the UI test mass and then release the UI test mass. There should now be two triples suspended side by side.				
70	Retract the blade stops in the top reaction mass and check the tip heights are correct.				
71	Retract the blade stops in the top test mass and check the tip heights are correct.				
72	Retract top stage blade stops.				
73	Carefully retract the stops on the top test mass, only retract them a little at a time and watch for pitch at all times. If the suspension appears stable and un-pitched then it is likely the blade tip stops are holding one of the blade tips down.				
74	Refer to Section [?? insert cross-reference] [?? there was no Appendix A in T060040-v1!] on fixing problems.				
75	As Step [?? insert cross-reference] but for the reaction mass.				

6.7 Final assembly

Step	What	Where	Time	People	Tools
76	Balance and align the quad to the point where both chains are at the correct height and are correctly pitched, and yawed. Note; alignment of the OSEMs will effect the pitch.				
77	Add the front and back plates to the tablecloth omitting the ECD and OSEM mounts.				
78	[?? Do we try putting on the sleeve? It probably has to come off again for storage.] Add sleeve.				

7 Storage

[?? work out how to get suspension into box and describe here]

8 Tools

Ian's list

Test stand:	Mechanical Test Stand mounted with Solid Stack Assembly
Manual fork truck:	Similar to Caltech Genie
Bench:	May be an optics bench but this is not mandatory
Tools:	All the appropriate hand tools and measuring devices
Masses:	These will be necessary to load blades flat.
Lower structure assembly tooling	
Wire jig	

Brett's list

$\frac{9}{32}$ inch nut driver or wrench for axial OSEM positioning.

$\frac{7}{16}$ inch nut driver or wrench for lateral OSEM positioning.

$\frac{9}{64}$, $\frac{3}{16}$, $\frac{1}{4}$, and $\frac{5}{16}$ inch allen wrenches.

A flat head screw driver for turning the top mass pitch adjusters.

Torque wrench for the blade clamp bolts capable of 400 in-lb (33 ft-lbs, 45 Nm).

Slip or block gauges for measuring 5 mm, 6.6 mm, and 12 mm gaps.

Dentist Mirror.

Flashlight or small lamp.

Structure pushers for rotating the structure on the optical table (see Figure 14).

5 axis table for safety while rotating the structure.

Lower structure tooling for use with the 5 axis table.

Safety goggles for working around the wires.

An optical alignment tool with 10 μRad accuracy, such as an autocollimator.

A small, light, reliable level to place on suspended masses (optional).

9 Useful procedures

9.1 Aligning the Brunson transit

Step	What	Where	Time	People	Tools
1	Set up the Brunson about 10’-15’ from the structure, with the telescope at very roughly the height of the mass to be clocked. If you get too close you won’t be able to see both ears/prisms/clamps and if you get too far away, the ears will be too small in the viewfinder to have their height read accurately. If there is a very large difference in height then you need to be careful that the structure is facing the telescope accurately (so that the ears/prisms/clamps are the same distance away), but this is not at all critical. Midway in height between the bottom mass and the penultimate mass is probably good enough, and gets you two clockings for the one setup.		30 min	2	
2	Make sure the lock on the vertical height adjustment is tight and that upper mechanism is firm against moderate horizontal pressure.		5 min	1	wrench: ¾” open-ended
3	Level the upper section as accurately as possible using the circular bubble level in the base of the rotating section.		5 min	1	
4	Turn the telescope pitch adjustment screw until it is roughly in the middle of its range.		1 min	1	
5	Unlock the telescope pitch clamp screw, roughly level the barrel of the telescope, and relock the clamp screw.		1 min	1	
6	Using the pitch adjustment screw, level the telescope as accurately as possible looking by eye at the barrel.		1 min	1	
7	Pick an opposing pair of the brass leveling discs in the leveling section and rotate the upper section until telescope is parallel with the line between the discs.		1 min	1	
8	Rotate the prism in the knurled housing near the top bubble level so that the aperture is at right angles to the telescope.		1 min	1	
9	Look into the prism aperture and adjust the long mirror to reflect the most ambient light into the side of the bubble level as indicated by the brightest view in the prism.		1 min	1	

Step	What	Where	Time	People	Tools
10	Adjust the pitch adjustment screw until both ends of the bubble can be seen in the prism and are aligned with each other.		1 min	1	
11	Rotate the telescope by 180°, and then rotate the prism by a further 180° to bring the aperture back to the original direction. Readjust the long mirror if necessary.		1 min	1	
12	Grip the telescope pitch adjustment screw knob and note its position. Keep careful track of the amount of adjustment required in the next step, either by keeping a grip on the knob (if the amount is not too great), or counting the number of quarter turns of adjustment.		1 min	1	
13	Adjust the pitch adjustment screw until both ends of the bubble are aligned in the prism.		1 min	1	
14	Back the pitch adjustment screw off to a point as near as possible to halfway between the initial and final positions.		1 min	1	
15	Redo the second half of the levelling using the the two brass discs identified earlier, rotating them in opposite directions, so as to tighten one as the other is loosened.		1 min	1	
16	Rotate the telescope another 180° and readjust the prism and long mirror. Hopefully the ends of the bubble will be very nearly aligned. Repeat the previous six steps until convergence is achieved.		5 min	1	
17	Rotate the telescope by 90° to align with the other pair of brass discs and repeat the previous seven steps.		15 min	1	
18	Rotate the telescope back to the line of the first pair of brass disks and check that the alignment in that direction has not been disturbed.		10 min	1	

9.2 Using the ergo-arm

Step	What	Where	Time	People	Tools

Step	What	Where	Time	People	Tools
1	Connect ergo-arm reservoir to vacuum pump with hose. [According to Mike Gerfen, the hose should be permanently band-clamped to the reservoir, with the quick release fitting at other end connecting alternately to pump and suction plate. We were doing this backwards, and the following procedure has been revised to reflect what we should have done.]		5 min	1	reservoir with hose, pump
2	Start pump, open valve at reservoir, evacuate reservoir to 30 psi, close valve, stop pump, disconnect hose.		1 min	1	reservoir with hose pump
3	Connect hose to ergo-arm suction plate.		1 min	1	
4	Close valve at suction plate, open valve at reservoir, monitor reservoir gauge for short time (e.g., 1 min) to check for stable pressure (i.e., no leaks in hose or connections).		2 min	1	
5	Bring suction plate near to mass and use horizontal, vertical, pitch and yaw DOFs to match position and angle.		5 min	4	
6	Hold suction plate firmly against mass and open valve at plate.		1 min	4	
7	Check that good suction has been achieved (reservoir pressure should still be around 23 psi). If the alignment was poor there will likely be no vacuum at all, in which case, repeat from the beginning, being more careful in Step 5.		1 min	1	
8	Close the valve at the suction plate, and then the valve at the reservoir. (The suction plate has a very slight leak and a small volume, so closing it requires constant attention to the pressure at the suction plate. If it drops it can be topped up by opening both valves momentarily. But if both valves are open and someone trips over the reservoir and pulls the hose off one of the connectors it's an instant catastrophe.)		1 min	1	
9	Raise mass, checking pressures at suction plate and reservoir regularly, and keeping a hand on the crankhandle at all times.		1 min	4	

END OF MAIN PROCEDURE

STUFF PAST HERE IS RAW MATERIAL FROM OTHER DOCUMENTS WHICH WILL GRADUALLY BE INTEGRATED ABOVE

10 Stuff from T080165-00 (Brett's balancing procedure) for plagiarizing

1 Related Documents

Numbers cited throughout this document refer to these documents.

1. Noise prototype Assembly procedure - T060040-05

URL:

http://www.eng-external.rl.ac.uk/advligo/Reviews/FRR/Documents/t060040-06.doc

Description:

This is the assembly procedure from RAL which should at this point be completed before balancing and alignment is to begin.

2. Quad Suspension Balancing and Alignment Procedure (UK Document)

URL:

http://www.eng-external.rl.ac.uk/advligo/Reviews/FRR/Documents/Quad suspension Balancing and Alignment procedure.doc

Description:

This document is the precursor to this updated procedure. It is a valuable reference since it contains additional details on how all the adjustments work and ideas on how to trouble shoot. This update should be considered a continuation, not a replacement.

3. Useful Data for Noise Prototype Quad Assembly (UK Document)

URL:

http://www.eng-external.rl.ac.uk/advligo/documents/Useful data for Noise Prototype Quad assembly.pdf

Description:

This document contains useful information about basic aspects of the quad such as weights, wire lengths and diameters, a description of how the blade tip positions are determined, and suspension stability.

4. Alignment Requirements for Quad - T080128-00-K

Description:

All the final alignment requirements for the quad are listed here.

5. AdvLIGO Quad Suspension Controls Prototype Suspension and Adjustment Method - T060039-00

Description:

This is the assembly and alignment procedure written for the quad controls prototype. Although the controls prototype clearly has some differences, many of the principles of aligning a quad are the same. As a result, this document is still a valuable reference of experience gained during the prototyping phases of the quad.

6. Holo-Krome Bolt Torque Data Sheet

URL:

http://www.holo-krome.com/pdf/techbk34-40.pdf

Description: This data sheet provides recommended bolt torque values from Holo-Krome.

7. Quad Pendulum Structure Pushers - T080230-00-0

Description:

This document provides additional detail on the use of the quad pendulum structure pushers used to align the quad structure on the seismic table.

2 Introduction

This document provides an updated set of instructions on how to balance and align the metal quadruple pendulum noise prototype, based on the experience gained at LASTI. It should be thought of as a continuation of ``Quad Suspension Balancing and Alignment Procedure'' referenced above. It assumes a basic understanding of the quad, but provides sufficient detail such that the document can stand alone from the assembly procedure. Thus, even someone who was not directly involved in the assembly process should be able to follow this document and produce a balanced and aligned quad.

There is no one 'best' way to align a quad. This procedure should only be thought of as a set of suggestions based on the experience gained thus far. The approach here is a bottom to top, coarse to fine approach. The bottom to top idea is that if you start with all the masses locked in a level configuration and rebalance them back to that level configuration as you suspend from the bottom up you will get a perfectly level, suspended pendulum at the end. The coarse to fine approach makes sense in the context of all the coupling between adjustments and is designed to minimize the number of iterations required to get a fully functional quad. It is because of these cross couplings and the constraints on the positions of the masses that simply suspending from the bottom up is not enough on its own. Likely there will be iterations between balancing the masses and aligning their positions. As a result, all the initial adjustments in this document are relatively quick and coarse to get everything in range. Then, when all the fine adjustments are made at the end, most of the alignment and balancing constraints will remain in tolerance and not need to be repeated.

3 Class B Tooling

$\frac{9}{32}$ inch nut driver or wrench for axial OSEM positioning.

$\frac{7}{16}$ inch nut driver or wrench for lateral OSEM positioning.

$\frac{9}{64}$, $\frac{3}{16}$, $\frac{1}{4}$, and $\frac{5}{16}$ inch allen wrenches.

A flat head screw driver for turning the top mass pitch adjusters.

Torque wrench for the blade clamp bolts capable of 400 in-lb (33 ft-lbs, 45 Nm).

Slip or block gauges for measuring 5 mm, 6.6 mm, and 12 mm gaps.

Dentist Mirror.

Flashlight or small lamp.

Structure pushers for rotating the structure on the optical table (see Figure 14).

5 axis table for safety while rotating the structure.

Lower structure tooling for use with the 5 axis table.

Safety goggles for working around the wires.

An optical alignment tool with 10 μRad accuracy, such as an autocollimator.

A small, light, reliable level to place on suspended masses (optional).

4 Hints Before You Begin

In general, the more carefully each assembly and alignment step is done, the easier later steps will become. For example, the more accurately the blade springs were installed during assembly, the easier it will be to balance pitch. The more precisely pitch is balanced on the first time through the alignment procedure, the fewer iterations will be needed to align all OSEMs, ECDs, and ESD.

While making adjustments on the quad make sure to watch out for touching stops and for interferences between the chains at every step. In particular the top masses have tight clearance around the blade spring clamp bolts. These bolts tend to get caught under the top plate of the opposing top mass if pitch and roll are not carefully aligned. There is nothing worse than spending an hour making adjustments only to discover that it was all for naught because a screw you did not see was touching one of the masses.

Remember that the blade springs magnify the tilts of the masses below them because their compliance allows for differential tilt between the masses.

Pitch is likely to cause a lot of trouble if the blade spring alignment within the rectangular masses is off. Pitch specifically is sensitive to errors in the blade assembly because any lateral misalignment of the blade tips away from the center of mass at each stage will generate a torque that will introduce a differential pitch between that stage and the one above it. If this problem is too extreme, it will be impossible to meet all the constraints of the OSEMs and test masses simultaneously, and the springs will need to be repositioned. Each blade tip should have exactly 5 mm of clearance on either side. Intolerable errors are on the order of a few tenths of a mm. More details on the spring positioning are in the procedure below.

5 Preparation

1. Put on safety glasses. Lock all the masses in level (by eye) position. Take care not to over stress the wires, especially the lowest ones since they are the most delicate and have no added compliance from springs.

Much of the leveling and balancing of the masses throughout this procedure can quickly and easily be gauged by eye. A small, light, and reliable bubble level is also useful. Figures 1, 2, and 3 show useful places to inspect by eye how level each mass is. Figure 15 in Appendix 10 illustrates the coordinate systems referenced throughout this document.

Figure 1: A quick and rough idea of the pitch of the 2 bottom masses is obtainable by inspecting the relative angle between each mass and the front/back edge of the structure. The red arrows indicate the gap between the main chain and front edge of the structure.

Figure 2: The pitch of the UI masses is visible by inspecting the relative angle between the mass's bottom plate and the stop mount bar indicated by the red arrow. This bar, along with the corresponding one on the other side, will also highlight roll by comparing the relative heights of the left and right sides of the mass.

Figure 3: The pitch of the top masses is visible by inspecting the relative angle between the top ECD arrays and the bottom of the adjustable top OSEM plate indicated by the red arrows. Roll is also visible by inspecting the relative height of the top mass with these references on either side of the structure.

2. Make sure all the final suspended bits are installed so that the masses have the correct balance and weight. For example, if the UI mass flag-magnet assemblies are not yet installed, it will be necessary to align the pitch of the entire suspension again when they are installed. Other things to check for are all flags, magnets and bolts. Also check that all pitch adjusters are centered. The UI and penultimate mass OSEMs must be installed to have the correct weight in each mass. The top mass OSEMs are supported by the structure and should not yet be installed, they will just get in the way later. If suspended bits are added to the masses, they should be weighed first, so that the final weights can be kept track of.

3. The orientation of the ECD magnets and shielded magnet pairs is important and should be double checked. The intention is to create magnetic dipoles in order to reduce the coupling of the magnets to stray fields. This means that the poles of the ECD magnets are placed in a checker board pattern around the top mass; see Figure 4. Two OSEMs around each top mass have shield magnets placed directly behind the coil magnet, the side OSEM and the OSEM at the front and center ('Side' and 'Face 1' respectively by LASTI notation). Additionally, the main chain UI mass has similar shield magnets behind the OSEM coil magnets. Figures 5 and 6 show the locations and orientations of the shielded magnet pairs.

Figure 4: This photograph shows the checker board pattern of the ECD magnet polarity. There is an identical pattern for the ECD magnets on top of the top mass. This photograph does not show the tablecloth simply because it was taken during the assembly stages.

Figure 5: This photograph shows the locations of the shielded magnet pairs around the top mass. In LASTI notation these are the magnets belonging to the 'Side' and 'Face 1' OSEMs. The UI mass OSEMs also have shielded magnet pairs.

Figure 6: The left photograph shows the orientation of the 'Face 1' OSEM magnet pair. Which side is north and which is south is arbitrary as long as two like poles are facing each other so that magnets tend to cancel. The side magnet pair, and the UI magnets in the right hand side picture function in a similar way.

6 Suspend and Balance the Masses

Start the alignment process on one chain at a time. Both can be done simultaneously, but experience proved that balancing one chain at a time is the most reliable. Later on it will be necessary to consider both chains simultaneously. The main goals here are to set the blade spring tip positions and set the differential pitch of all the masses. It is important to make sure early on that the differential pitch is no greater than a few mRad.

1. Choose a chain and release the bottom mass. It should stay level and have the same pitch and roll as the penultimate mass. If this is not true, the wires have not been made or clamped properly and should be changed.

2. Release the penultimate mass. If you are on the main chain, both lower masses should now hang free and level in pitch on their own. If you are on the reaction chain, you may have to adjust the penultimate mass pitch adjuster to bring both masses to a level state. Figure 7 describes this adjuster. Errors in pitch are likely due to the errors in the wires. Errors in roll may be due to blade spring tip heights, which will be sorted next.

Figure 7: The reaction chain penultimate mass has a large pitch adjuster indicated by the red arrow. The long diagonal screw is a lock. If the lock is loosened the adjuster will slide back and forth altering pitch.

3. While the UI mass is still locked, release the blade spring tip stops and adjust the spring tip height to set the vertical height (d parameter in model). The blade tip height should be 12 mm from its reference point. Instructions for adjusting the height are in Figure 8. There should also be 5 mm of clearance on either side of the blade tip, as shown in this figure [3]. If the clearance is off by more than a few tenths of a millimeter the spring may have to be adjusted, which may not be allowed in situ for risk of undoing a heat treatment of the blade spring. Note that if the UI mass is not locked in a level position the wires will pull on the tip making it appear malpositioned even if it is not. The two lower masses should now be level in both pitch and roll.

Figure 8: The left photograph shows the vertical blade tip reference points indicated by the red arrows. The arrows are pointing to a lip on one of the two upright U shaped aluminum parts that arch over the blade tip. For the UI mass, there should be 12 mm between the top of the blade and that lip when the round masses are suspended below. There should also be 5 mm of clearance on either side between the tip and these U shaped parts [3]. The right photograph shows the adjusting arm for the blade tip height. Just above the left red arrow is a long upright $\frac{1}{4}$-20 bolt. Turning this bolt will adjust the angle at which the blade leaves its clamp, allowing the tip to move up and down. It may be necessary to slightly loosen the two outer bolts in the clamp (the ones closest to and furthest from the opposing chain). The UI spring clamp bolts should be torqued back to 100 in-lbs (8.3 ft-lbs, 11.3 Nm) [6]. The top mass springs are referenced and adjusted in a similar way. The top mass clamp bolts get torqued to 330 in-lbs (27.5 ft-lbs, 37.3 Nm) [6].

4. Problems are most likely to become visible when releasing the next two stages. Release the UI mass. At this point any significant pitch is likely due to lateral offsets on the blade spring tips. If the pitch is small enough you can compensate by repositioning some of the removable mass. If it is off by a large amount the spring will have to be repositioned. At the time of writing it is still uncertain whether repositioning the spring in situ will be an option because of a risk of undoing a heat treatment of the spring. If it is an option, the spring clamp bolts can be loosened and the spring tip can be forced to slide back and forth. The mass should be locked while making this adjustment. Make sure to retighten the bolts when the adjustment is complete. Clamp torque values are listed in Figure 8 and Appendix 9.

5. Before releasing the top mass check the blade tip positions in the same way that they were checked on the UI mass. The vertical height should be 6.6 mm from the reference lip, and the lateral position should again allow 5 mm of clearance on either side [3].

6. Release the top mass. Check to make sure the other top mass is not interfering, see Figure 9. This stage has additional options to compensate for pitch errors. There are two coarse pitch adjusters underneath the top mass that slide the attachment of the top wires along the bottom plate. There are also two fine pitch adjusting 'screws' on the top mass as well. One is below the bottom plate, the other above the top plate behind the center OSEM. These can be turned in and out to adjust the pitch balance. See Figure 10. You should only use the coarse adjusters if the fine adjusters run out of range. Please note that using them will introduce a yaw and longitudinal displacement. These yaw and longitudinal offsets can be compensated for by adjusting the top stage springs, but doing so may impose additional pitch-roll coupling, making damping and control more difficult.

Ideally you should now have a level suspension chain with no differential pitch between the masses. A small amount of differential pitch below a few mRad is OK. If this is the case, keep the top masses as level as possible for the time being since the next few steps will require it.

Figure 9: The clearance between the blade clamp bolt heads of one top mass and the top plate of the opposing top mass is small. When adjusting the top mass positions, always keep this possible interference in mind. This picture shows one of 4 possible windows to inspect the clearance. Getting the roll of each chain correct will help prevent pitch headaches later on since both of these adjustments alter the amount of space here.

Figure 10: The left photograph shows the fine pitch adjusting screws. The tablecloth is not in place to show the pitch adjusters. The right photograph shows one of the two coarse pitch adjusters. The coarse adjusters should only be used if the fine adjusters have insufficient range. They work by moving the attachment points of the top wires. To use them, loosen the 3 $\frac{1}{4}$-20 bolts (one is hidden inside the center block) and turn the 2 $\frac{1}{4}$-20 pusher-puller screws to slide the adjuster forwards and backwards. Retighten the bolts after completing the adjustment.

7. The second chain should now be suspended. If it interferes with the first because of global roll, yaw, or longitudinal errors, the first chain should simply be held out of the way with stops. These offsets will be dealt with in the next section.

7 Align the Chains

The following steps will now guide the alignment of the chains relative to each other, the structure, and the global coordinate system (i.e. pitch and yaw of the test masses). Virtually all adjustments at this point will couple to each other, so there will likely be some iterating back and forth until everything is met within its constraints.

1. Install the OSEM mount plates and set them to the center of their range. In the next few steps this will allow you to quickly inspect the alignment of each chain relative to the structure, help ensure that all the plates have enough range to adjust the OSEMs, and roughly set the spacing between the chains. See Figure 11.

Figure 11: This figure shows one of the OSEM plates without the OSEM. Centering the plate on the structure using the 3 copper cams will allow you to quickly eyeball longitudinal, yaw, vertical and roll of the top masses relative to the structure

2. Assuming the pitch of the top masses are roughly leveled, the offsets of the flags and magnets from their midpoints in the OSEM plates will tell you about longitudinal, yaw, vertical and roll relative to the structure. Use the top stage blade springs to adjust these degrees of freedom. Any transverse offset will also be visible, however there is no adjustment for this degree of freedom because there needs to be a gross error, likely in one of the top wires, for this to be the case. If so, wires may need to be remade.

3. Make sure all the spring stops are free. Roll and vertical can then be adjusted by packing the 0.5 mm and/or 1.0 mm shims underneath the blade tip clamps. These shims only allow one to raise, not lower one side of a chain at a time. If the chain appears too high, the masses may not be heavy enough, some wires were set too short, the tablecloth was not assembled correctly, or possibly the springs are stiffer than the design. See Figure 12.

Figure 12: The red arrow points to a top stage wire clamp with shims packed underneath to alter the height of one end of the suspension. To insert these shims the clamp needs to be removed which requires giving the wire some slack by either raising the top mass or lowering the spring.

4. Adjust the yaw and longitudinal degrees of freedom using the top stage rotational adjusters. See Figure 13. To make this adjustment the top mass should be locked and the outer top stage blade clamp bolts loosened (the ones closest to and furthest from the opposing chain). The rotational adjuster has a push-pull bolt pair setup at the back of the spring to rotate the tip. The blade pivots near its midpoint, so tightening the pulling screw moves the tip away from you while tightening the pushing screw brings it toward you. After each adjustment resuspend to check the alignment. Set the space between the test masses close to 5 mm. The spacing will be fine tuned further down the procedure. When finished, tighten the pusher and puller bolts to lock the blade spring in place and torque the clamp bolts back to 330 in-lbs (27.5 ft-lbs, 37.3 Nm) [6]. The blade spring rotation may need to be tweaked again later on to optically align the test mass, but that will be a quick adjustment if this is done properly first.

Figure 13: To rotate the top stage blade springs first lock the top mass and then loosen the two outer bolts indicated. The spring rotates by means of the push-pull bolt pair system shown at the back of the spring. The blade pivots near its midpoint, so tightening the pulling screw moves the tip away from you while tightening the pushing screw brings it toward you.

5. Before moving onto the optical alignment, double check there are no interferences preventing the suspensions from resting in their natural positions. This includes checking all the stops, all around the tablecloth, and the spaces between the masses. The most rigorous check is to install OSEMs and measure transfer functions; however the OSEMs will likely need to come out again to continue the alignment procedure, since they themselves can introduce interference and at best will need realigning later. Nonetheless, installing one or two OSEMs is not much work and damping loops can make the final yaw alignment go much faster, so the preferred option can be chosen on a case by case basis. Section 8 describes how to install OSEMs.

6. The next two steps concern the optical alignment of the test mass. The main chain test mass should be aligned to within 100 μRad in pitch and 10 μRad in yaw. Yaw is conceptually the simplest and also the most stable, so it should be done first. Yaw can be roughed to 1 mRad by turning the entire structure with a couple of structure pushers anchored to the optics table, see Figure 14. The 5 axis table should be placed under the quad for safety. Using the 5 axis table requires installing the lower structure tooling around the lower structure of the quad. The table should not take the full weight of the quad because the lower structure was not designed to take the full weight of the upper structure (testing shows that it can, but there is a small risk of deforming the structure). The adjustment is done by loosening the dog clamps and adjusting the pushers until yaw is set within 1 mRad. If you do better than 1 mRad at this point you will likely lose it when you tighten the dog clamps. The remainder of the alignment can be achieved by using the top stage spring rotational adjusters. Alternatively, light tapping on the blade tips with a hammer may be sufficient to take up the last mRad. The reaction chain should be aligned such that its test mass is within 5 ± 0.25 mm of the main test mass in yaw and longitudinal. At the time of writing this document the method for measuring this gap is still being reworked. Previously it was simply done with a 5 mm slip gauge or shim, preferentially with some damping loops running. Torque the blade spring bolts with the torque wrench up to 330 in-lb (27.5 ft-lbs, 37.3 Nm) [6].

Figure 14: The entire structure should be rotated to further tune the main test mass yaw to within 1 mRad (after the top mass yaw has been aligned to the structure). This photograph shows one of the structure pushers that are useful for rotating the structure. To make this adjustment the dog clamps need to be slightly loosened. The 5 axis table should be placed under the lower structure (with the lower structure tooling) for added safety, however it should not take the full weight of the suspension because the lower structure is not designed to support the weight of the upper structure. To use this adjuster simply bolt it to the optics table with the large bearing tipped screw (black screw in this picture) facing the structure. When the screw is in contact with the structure tighten it to push on the structure [7].

7. A note about pitch hysteresis: pitch has the added complication of a hysteresis problem related to the wires which will cause the pitch alignment to drift. The sizes of the drifts are proportional to the amplitude of mass oscillations and inversely proportional to damping time. Thus, if the quad is given a large bump where the masses repeatedly bang into the stops and each other, the pitch alignment may find a new equilibrium which will need to be adjusted. For similar reasons, damping loops should not be used while making pitch adjustments. Small drifts can be removed by allowing the suspension to oscillate freely for a few minutes.

8. To remove any hysteresis effects tap on one of the masses from each chain to set a pitch oscillation of a couple mRad. Allow the oscillation a few minutes to ring down. Pitch should now be close enough to be within range of the fine pitch adjusters. With a flat head screw driver, turn one of the main chain adjusters until pitch is within 100 μRad. Because of hysteresis there is no sense in doing better than 100 μRad. Adjust the reaction chain test mass to follow. The comments from step 6 on measuring the gap between the test masses apply here as well, with the caveat that damping loops may be undesirable because of the hysteresis problem.

9. Check again that everything is fully suspended.

8 OSEMs and Eddy Current Dampers (ECDs)

The experience at LASTI at the time of writing this document is that the clearance between the magnet-flag assembly and the inner bore of the OSEM is extremely tight and the assembly will often make contact with that inner bore. The vertical OSEMs on top of the tablecloth are most likely to present trouble since it is difficult to see inside the bore. Thus, they should be the last OSEMs installed and the first suspected for interference. New OSEMs with larger bores will be in use by the time assembly at the sites begins, which will alleviate this concern somewhat.

This section is also where it will be most obvious how well the previous steps have been done. If everything went carefully and smoothly, this section should not pose a problem. If not, the OSEMs will not have enough range and it may be necessary to repeat some earlier steps.

1. Plug in the 12 top mass OSEMs. Organize them, so that all the serial numbers appear in the same order as the OSEMs do in the software, and ideally make sense spatially on the quad. This will make life much easier if OSEMs need to be repeatedly removed and replaced. Make a note of all the DC open light voltages. They will need to be aligned to their respective midpoints later.

2. Starting with one at a time, install the OSEMs and zero them out ($< 2\%$ of the open light voltage). This step will involve both the axial adjustment of the OSEM and lateral adjustment of the mounting plate using the copper cams. Zeroing them makes sure they are aligned correctly with respect to the flag. Try to keep the ECD magnets centered when adjusting the OSEM plates. Also, keeping them at zero until all the OSEMs are in makes it more obvious when one of them begins to touch a magnet or flag since the voltages will tend to shift away from zero when this happens.

3. Once all the OSEMs are in and zeroed, bring them out to half their respective maximum voltages.

4. Measure transfer functions to ensure that there is no interference anywhere on the suspension. Make reference transfer functions for comparison later. Appendix 10 provides sample transfer functions.

5. Install the copper ECDs. The pin in the center of each 4 magnet group is designed such that it will hit the ECD before the magnets do. Consequently, it functions as both a stop and a check on the ECD alignment. This step is at the end of the procedure because damping is one of the signs for interference (such as a rubbing stop). The ECDs also introduce an additional source of interference. Thus, it will be easier to install these once everything else is taken care of first.

6. Measure transfer functions again to check that the ECDs are functioning properly.

Appendix

9 Useful Balancing and Alignment Data

Table 1 contains a summary of useful data needed to meet the alignment requirements for the metal suspension. Most of these parameters also apply to the glass suspension, those that do not are labeled with a * or **.

Parameter	**Measurement**
UI blade spring tip height [3]	12 mm
UI blade spring lateral position [3]	5 mm
UI blade spring clamp bolt torque [6]	100 in-lbs (8.3 ft-lbs, 11.3 Nm)
Top mass blade spring tip height [3]	6.6 mm
Top mass	5 mm

blade spring lateral positions [3]	
Top mass blade spring clamp bolt torque [6]	330 in-lbs (27.5 ft-lbs, 37.3 Nm)
Top stage blade spring clamp bolt torque [6]	330 in-lb (27.5 ft-lbs, 37.3 Nm)
Main chain test mass pitch *	$\pm 100\ \mu$ Rad
Main chain test mass yaw [4]	$\pm 10\ \mu$ Rad
Reaction test mass to main test mass **	5 ± 0.25 mm around the circumference

Table 1: Table of useful balancing and alignment parameters. All the blade spring measurements are relative to the references discussed in Section 6. * The glass test mass pitch tolerance is $\pm 10\ \mu$ Rad [4]. ** The glass reaction test mass still needs to be spaced 5 ± 0.25 mm from the main test mass, however the parallelism requirement tightens to $\pm 100\ \mu$ Rad [4].

10 Sample Transfer Functions

Figure 15 illustrates the coordinate system referenced in this document and used in the following transfer functions in Figures 16 through 21. These transfer functions make good initial references while checking for interferences and debugging. Each suspension should eventually have a set of its own reference transfer functions. All the transfer functions here are measured only from the main chain since the reaction chain is nearly identical.

The preference for measuring transfer functions on the quad at LASTI has been to use either a white noise excitation or a Schroeder multi-sine excitation. Both of these methods are broadband and allow the entire interesting spectrum (0.1 Hz to 10 Hz) of the quad to be measured simultaneously. Using these methods, quick transfer functions are measurable in a few minutes or less which provide sufficient detail to search for interferences or debug. The Schroeder multi-sine excitation is the quickest because it injects many known sine waves simultaneously throughout the spectrum, thus providing enhanced coherence over white noise. The sample figures below, with the exception of pitch, were measured with the Schroeder approach (each measured over a few hours). Pitch, Figure 20, was measured with white noise.

Figure 15: The coordinate system of one of the rectangular masses. All the masses have similar coordinate systems.

Figure 16: An x to x transfer function from the main chain top mass.

Figure 17: A y to y transfer function from the main chain top mass.

Figure 18: A z to z transfer function from the main chain top mass. The 4th vertical mode is near 17 Hz and is not observable from the top mass. The 4th mode exists mostly as the vibration of the wires between the two round masses.

Figure 19: A yaw to yaw transfer function from the main chain top mass.

Figure 20: A pitch to pitch transfer function from the main chain top mass.

Figure 21: A roll to roll transfer function from the main chain top mass.

11 Stuff from T0900055 (MB's LASTI rehang procedure) for plagiarizing

Step	What	Where	Time	People	Tools
1	Lock all masses. Stops need only be done up gently – touching plus 1/8 turn. Putting divots in the metal is unnecessary. (The "2+1" in the "People" column refers to the the fact that all in-tank operations need at least one support person outside.)	in BSC	10 min	2+1	hex keys
2	Disconnect electrical wiring to lower structure and masses and tuck ends	in BSC	5 min	2+1	

Step	What	Where	Time	People	Tools
	safely out of the way.				
3	Lock top stage, lock top mass blades.	in BSC	5 min	2+1	hex keys
4	Raise stops under UIM to touch and overload UIM blade tip by 3mm.	in BSC	5 min	2+1	hex keys
5	Raise UIM until top to UIM wires are slack.	in BSC	5 min	2+1	hex keys
6	Remove UIM pitch mass (to allow access to screws in next step).	in BSC	5 min	2+1	hex keys
7	Disconnect wires from top mass to UIM at UIM.	in BSC	5 min	2+1	hex keys
8	Remove face earthquake stops.	in BSC	5 min	2+1	hex keys
9	Remove X braces and sleeve first, then ¼-20 bolts and spacers at the bottom of the sleeve, then 3/8-16 bolts up top. Loosen all the ¼-20 bolts at the bottom of the sleeve before removing them so that removing the spacers behind them is easier with less risk of dropping them on the optics.	in BSC	30 min	3+1	hex keys
10	Install conveyor, five-axis table and elevator (this was done first in reality which made it not quite impossible but very difficult to get the sleeve off). [Rich: conveyor through-holes to the door flange should be opened up so not so tight.] Make sure elevator is installed on 5 axis table such that you have +- 180^o of rotation. Wrap electrical cabling for elevator in UHV foil.	in, near BSC	1 day	4	5AT, conveyor
11	Remove side plates on elevator on five-axis tooling and rotate elevator so that it can be slid around structure on the conveyor. When elevator is around structure, rotate so that side labeled “2” is on main chain side.	in BSC	10 min	2+1	wrench
12	Insert halves of (lower structure assembly tooling) LSAT around the structure, hooking them on the pins on top of the fully retracted pushers of the five-axis table. To make this easier, start with some half-inch spacers at the bottom of the elevator to lift the LSAT above the pusher	in BSC	5 min	2+1	½” spacers

Step	What	Where	Time	People	Tools
	pins. These spacers will allow the LSAT to be pushed together before lowering it onto the pusher pins.				
13	Lock the halves of the LSAT together with plates and bolts, except at the bottom level (where this will cause interference with the sides of the elevator).	in BSC	5 min		LSAT side plates
14	Reinstall side plates on five-axis table, aligning "1" on corner of first plate to matching "1" on table and "2" on second plate to "2" on other side of table. Bolts are best inserted from centre outwards. Finger-tight is fine. (Doug says: need better tolerancing on holes.)	in BSC	5 min	2+1	5AT side plates, bolts
15	Raise LSAT on pushers until it almost engages with the structure.	in BSC	5 min	2+1	
16	Adjust the various DOFs of five-axis table as appropriate until the top of the LSAT is well-aligned in position and angle with the lower structure.	in BSC	5 min	2+1	
17	Raise pushers until the LSAT has fully engaged with the lower structure and the weight is off the implementation ring.	in BSC	5 min	2+1	
18	Replace face stops on both chains.	in BSC	10 min	2+1	hex keys, face stops
19	Unbolt implementation ring from upper structure and remove bolts from upper to lower structure.	in BSC	10 min	2+1	hex keys
20	Retract pushers fully, lowering lower structure.	in BSC	5 min	2+1	
21	Insert translational locking pin into 5 axis table. (This must happen after disconnecting the lower structure because the table position may need to be adjusted to get the pin in place.)	in BSC	5 min	2+1	pin
22	Unbolt implementation ring from lower structure (because otherwise it won't get through the door).	in BSC	10 min	2+1	hex keys
23	Move lower structure to door of tank on conveyor.	in BSC	5 min	2+1	

Step	What	Where	Time	People	Tools
24	Remove side plate on five-axis table on the main chain side ("2").	near BSC	5 min	2	hex keys
25	Bring in Genie (avoiding bumping the HEPI) so that the forks are below the uppermost of the side plates on the LSAT. Use spacers (approximately ½" thick) on top of the forks near the tips to allow for sag of the forks under load.	near BSC	5 min	4	Genie, ½" spacers
26	Lift the LSAT off the five-axis table onto the cart, install remaining (bottom) plates holding together the two haves and clamp it down.	near BSC	10 min	4	cart, LSAT side plates, dogs
27	Cover the LSAT on the cart with a door cloth and wheel to the assembly area.	in transit	5 min	4	door cloth
28	Manhandle Genie past solid stack to assembly area.	in transit	5 min	4	
29	Bring in Genie as before and take LSAT off cart using ½" spacers for sag (but don't set it down yet).	assembly area	5 min	4	Genie, ½" spacers
30	Disconnect lowest set of bolts joining the two halves of the structure (these are difficult to remove later).	assembly area	5 min	4	hex keys
31	Set LSAT down on foil-covered pallet with ¼" spacers. (Use enough spacers that each half is stable independently.)	assembly area	5 min	2	pallet, (lots of) ¼" spacers
32	Remove plates holding halves of LSAT together.	assembly area	5 min	2	hex keys
33	Remove remaining bolts holding halves of structure together.	assembly area	5 min	2	hex keys
34	Bring in Genie as before except placing ¼" spacers near the base of the forks so as to enable just the reaction chain to be picked up.	assembly area	5 min	4	Genie, ¼" spacers
35	Take weight of reaction chain with Genie and remove ¼" spacers under it. Withdraw straight back so as to cleanly disengage pins aligning two halves.	assembly area	5 min	4	Genie

Step	What	Where	Time	People	Tools
36	Set reaction chain on a second foil-covered pallet (or piece of foil on the floor), remove spacers and pick up the reaction chain again closer to the centre of the forks.	assembly area	5 min	4	Genie, pallet #2, foil
37	Move the reaction chain to the turntable.	assembly area	5 min	4	breadboard on 10" blocks, turntable
38	Rotate reaction chain 180°, apply safety chocks under turntable to minimize rocking.	assembly area	5 min	4	chocks
39	Disconnect suspension wires between UIM and PM and between PM and (dummy) ERM.	assembly area	5 min	2	
40	Attach ergo-arm adapter plates to PM.	assembly area	10 min	2	adapter plates, bolts, hex-keys:
41	Bring in ergo-arm (see Section 9.2), move PM to work table (double-check weight etc).	assembly area	20 min	4	ergo-arm, vacuum pump, hose, reservoir
42	Remove dummy ERM with adapter plates and ergo-arm.	assembly area	30 min	4	adapter plates
43	Weigh CP and prepare replacement PRM with appropriate mass.	assembly area	30 min	2	CP
44	Install replacement PM using adapter plates and ergo-arm.	assembly area	30 min	4	adapter plates, ergo-arm
45	Install new wire assemblies incorporating UIM-PRM wires and wire loops for CP.	assembly area	10 min	2	pre-made wire assembly, hex-keys
46	Set up the Brunson transit on opposite side from ergo-arm access direction.	assembly area	30 min	1	transit
47	Using the transit, clock the PRM until the clamps on either side are at the same height.	assembly area	10 min	2	transit
48	Prepare the CP, soldering on the tabs and electrical wires per Section **Error! Reference source not found.**. (This step could be done at any	clean room	1 day	1	tabs, coax, indium, Al buttons, soldering

Step	What	Where	Time	People	Tools
	convenient time prior.)				iron, nitrogen blower
49	Bring the CP into the assembly area and stand it up in a V-block with the non-ESD face accessible. (This was done manually, which is not ideal. On the other hand it's not clear that it could have been done with the ergo-arm because once the tabs and wiring are added, the CP can only be laid with the non-ESD face down, and one might worry that the tabs would prevent the suction plate from sealing on the ESD face – this needs to be tested.)	assembly area	10 min	2	V-block
50	Arrange a foil pouch (about 9"x9") near the bottom of the structure on the back (transit) side for receiving and keeping safe/clean the CP electrical wires.	assembly area	5 min	1	foil
51	Fit the silica-tips to upper earthquake stops but leave them fully retracted.	assembly area	10 min	2	silica [PTFE] tips
52	Put type "D" chocks under the lower pads.	assembly area	10 min	2	type "D" chocks
53	Bring the suction plate of the ergo-arm up to the non-ESD face of the CP with the T-piece between the valve and gauge at about 22.5° (so that in a later step it will fit into the corner of the octagon of struts defining the CP's position in the structure).	assembly area	5 min	4	ergo-arm
54	Pick up the CP with the ergo-arm, assigning a person to support the ESD wires throughout the next few steps.	assembly area	5 min	4	ergo-arm, vacuum pump, hose, reservoir
55	Bring the ergo-arm with the CP near the structure, and adjust the angle of the base and the height, lateral position, pitch and yaw of the head so that the CP is ready to pass through the structure neatly, with approximately equal clearance on all sides. Lock the castors of the ergo-arm.	assembly area	5 min	4	ergo-arm
56	Roll the CP so that the T-piece is at 12 o'clock. (This will put the prisms	assembly area	1 min	4	ergo-arm

Step	What	Where	Time	People	Tools
	and ESD wiring tabs in line with corners of the octagon of struts.)				
57	Pull the two loops of suspension wire gently out of the octagon at the far side of the structure and assign a person to hold them up out of the way for the next few steps.	assembly area	1 min	4	ergo-arm
58	Pass the ESD wiring carefully through the structure and place it in the foil pouch.	assembly area	1 min	4	foil pouch , ergo-arm
59	Move the CP carefully into the structure until the leading face, the ESD wiring tabs and the prisms have all fully entered the structure volume and are clear of the front-face struts.	assembly area	5 min	4	ergo-arm
60	Roll the head back to the original position with the prisms at 3 o'clock and 9 o'clock, and the T-piece at 22.5°.	assembly area	1 min	4	ergo-arm
61	Continue to move the CP into the structure either until it has reached its design position with the ESD face level with the far side of the structure or until the T-piece is about to foul on the near side of the structure.	assembly area	5 min	4	ergo-arm
62	Thread the pouch of ESD wiring up through the loops of suspension wire and lower the suspension wires against the far side of the structure.	assembly area	1 min	4	ergo-arm
63	Stretch the suspension wire loops around and under the mass, being especially careful not to snag them on the ESD wiring tabs. Route them between the pairs of upper earthquake stops on each side.	assembly area	1 min	4	ergo-arm
64	Lower the CP gradually until the wires are pulled straight but not taut. If the T-piece on the suction plate fouled against the structure earlier and additional insertion is required, it will tend to become possible at this stage – alternate small downward and inward steps as appropriate.	assembly area	1 min	4	ergo-arm
65	Nudge the wire loops into the grooves on the prisms and around the bottom of the CP. A mirror placed facing up on the turntable below the	assembly area	1 min	4	mirror, ergo-arm

Step	What	Where	Time	People	Tools
	structure will make it easier to check that this has been done correctly.				
66	Using the transit, adjust the CP in roll until the prisms are at the same height.	assembly area	10 min	4	transit
67	Continue to lower (and if necessary, further insert) the CP until the wires are taut and/or it rests on the bottom earthquake stops.	assembly area	1 min	4	ergo-arm
68	Screw in the upper earthquake stops to a 0.5 mm gap.	assembly area	5 min	4	
69	Position a person to restrain the CP in case it swings front to back. Have another person remove the vacuum hose, open the valve on the suction plate and withdraw the ergo-arm.	assembly area	5 min	4	ergo-arm
70	Back off the upper earthquake stops, insert Teflon pads and screw them back in to touch.	assembly area	5 min	2	Teflon pads
71	Install the face stops and screw them in to a 0.5 mm gap.	assembly area	5 min	2	face stops
72	Take out the chocks under the turntable and rotate the reaction chain by 180°.	assembly area	5 min	4	
73	Using the Genie, move the reaction chain off the turntable and place on pallet with approx ¼” spacers underneath. [In fact we used some of the plates for holding the halves of the LSAT together, which was a bad idea because we had to muck around later getting them out. Purpose-made would be better.]	assembly area	30 min	4	¼” spacers
74	Check reaction chain for balance per Section 6.4.	assembly area	45 min	2	triple-hang tooling, hex keys
75	Route the ESD wiring up the chain. There need to be wire clamps at top and bottom of the back face of the PRM.	assembly area	30 min	2	ESD wire clamps
76	Using the Genie, put the main chain on the turntable with the outside of	assembly area	20 min	4	Genie, turntable

Step	What	Where	Time	People	Tools
	the LSAT towards the transit and the centre side toward the access side.				
77	Remove the UIM-PM and PM-TM wires.	assembly area	5 min	2	
78	Using the ergo-arm and adapter plates, remove the PM and TM and double-check weights etc.	assembly area	30 min	4	balance
79	Prepare new PM with appropriate mass.	assembly area	30 min	2	balance
80	Install the new PM with adapter plates and ergo-arm.	assembly area	30 min	2	adapter plates, ergo-arm
81	Install the wire assembly as for the reaction chain.	assembly area	10 min	2	pre-made wire assembly, hex-keys
82	Release overload on UIM blades until PM suspends and check for balance. Restore overload.	assembly area	10 min	2	hex-keys
83	Clock PM with transit.	assembly area	10 min	2	transit
84	Put silica tips on upper TM earthquake stops but leave well retracted. Install silica tipped face stops.	assembly area	5 min	2	hex-keys
85	Put type “A” adjustable pad spacers under lower earthquake pads.	assembly area	10 min	2	type “A” spacers
86	Install ring heater, leaving halves as far apart as possible (for the biggest possible gap in the centre).	assembly area	20 min	2	ring heater, bolts, hex-keys
87	Pick up TM with ergo-arm from AR side. (Angle of T-piece doesn’t much matter.)	assembly area	10 min	4	ergo-arm, pump, hose reservoir
88	Insert TM into structure, being *extremely* careful not to bump prisms on ring heater, stopping when ergo-arm side is level with face of structure. Position wire loops around TM as it passes through. (Joe says: could try tilting to put prisms at 6 and 12 o’clock.)	assembly area	10 min	4	ergo-arm

Step	What	Where	Time	People	Tools
89	Lower TM until wires are straight but not taut.	assembly area	5 min	4	ergo-arm
90	Dress wire loops to pass through prism grooves and then neatly under TM. Again, a mirror is convenient.	assembly area	5 min	4	mirror
91	Lower TM onto pads, remove ergo-arm.	assembly area	5 min	4	
92	Put Teflon pads between upper earthquake stops and mass for both PM and TM and tighten stops.	assembly area	5 min	2	Teflon pads, hex keys
93	Pick up main chain with tips of Genie forks, using thin spacers (≈1/4") on tip side to counteract sag.	assembly area	10 min	4	Genie, ¼" spacers
94	Bring main chain over to pallet #2.	assembly area	5 min	4	Genie
95	Check main chain for balance per Section 6.4.	assembly area	45 min	2	triple-hang tooling
96	Remove First Contact from AR face of TM.	assembly area	5 min	2	razor blade
97	Pick up main chain with tips of Genie forks, using thin spacers (≈1/4") on tip side to counteract sag. Bring over to reaction chain on pallet #1.	assembly area	10 min	4	Genie, ¼" spacers
98	Match height first then bring in horizontally to mate locating pins. Insert ¼" spacers under main chain and then set down.	assembly area	10 min	4	Genie, (more) ¼" spacers
99	Attach plates holding LSAT together.	assembly area	5 min	2	hex-keys
100	Pick up whole LSAT with Genie, using thick spacers (≈1/2") to counteract sag.	assembly area	5 min	4	Genie, ½" spacers
101	Transfer LSAT to cart, clamp down, cover, and wheel to tank.	in transit	15 min	4	cart, hex keys, dogs
102	Manhandle Genie past solid stack to tank area.	in transit	5 min	2	Genie
103	Pick up LSAT with tips of forks using ½" spacers	near BSC	5 min	4	Genie, ½" spacers

Step	What	Where	Time	People	Tools
104	Take off lower plates connecting halves of LSAT. (These will foul on the elevator of the five-axis table.)	near BSC	5 min	2	hex keys
105	Remove one side-plate ("2") from elevator of five-axis table.	near BSC	5 min	2	wrench
106	Place LSAT into elevator of five-axis table (avoiding bumping the HEPI with the Genie). The LSAT should be positioned vertically a few mm above the floor of the elevator and horizontally with locating holes directly above locating pins on pushers.	near BSC	10 min	4	5AT, elevator
107	Raise pushers to engage pins and support LSAT. Remove Genie.	near BSC	5 min	2	
108	Install side plate on elevator on five-axis table (matching corner "1" or "2" and inserting bolts from centre as before).	near BSC	5 min	2	wrench
109	Lower LSAT until it is almost sitting on floor of elevator (so that it will go through door).	near BSC	5 min	2	
110	Roll table into chamber on conveyor.	near BSC	5 min	2+1	
111	Attach implementation ring to lower structure.	in BSC	10 min	2+1	hex keys
112	Raise pushers until lower structure is about to contact, adjusting five-axis table DOFs as necessary to achieve a good mate.	near BSC	5 min	2+1	
113	Connect implementation ring to upper structure and install through bolts, using washers under the through bolts.	in BSC	10 min	2+1	implementation ring, hex keys
114	Remove remaining plates holding halves of LSAT together.	in BSC	5 min	2+1	hex keys
115	Remove upper two face stops on PM on both main and reaction chains.	in BSC	5 min	2+1	hex keys
116	Put two long spacers (1" thick) on floor of elevator.	in BSC	1 min	2+1	1" spacers

Step	What	Where	Time	People	Tools
117	Lower pushers till LSAT comes to rest on spacers.	in BSC	2 min	2+1	
118	Using two people per side simultaneously, pull the halves of the LSAT out and remove.	in BSC	2 min	4+1	
119	Remove UIM upper pitch mass (both chains).	in BSC	10 min	2+1	hex keys
120	Connect wires from top mass to UIM (both chains).	in BSC	5 min	2+1	hex keys
121	Install UIM upper pitch mass (both chains).	in BSC	10 min	2+1	hex keys
122	Remove five-axis table and conveyor.	in BSC	1 hour	4	??
123	Install two extra planks of flooring in the tank so there are two on each side and bring in the table to give easy access to top mass.	in BSC	1 hour	4	??
124	[This shouldn't be necessary! The ends of the glass rod in the upper half of the ring heater stuck out too far on each side and fouled on the sleeve. Assuming the radius of the curved section in the prototype was right, the welded on sections should be 20-25 mm long to serve their purpose but not foul.] Loosen the set screws holding the glass rod in the top half of the ring heater. Push one end of the rod in about 3 mm and tighten the set screw. Carefully push the other end of the rod in twice as far (bending the glass rod to a tighter radius!) and tighten that set screw.	in BSC	10 min	2+1	hex keys
125	Remove all face earthquake stops on the bottom two levels of both chains.	in BSC	10 min	2+1	hex keys
126	Bring in the sleeve, lift it up around the structure and bolt it on. [Need to rethink washers.]	in BSC	10 min	2+1	hex keys
127	Install X braces.	in BSC	10 min	2+1	hex keys
128	[This shouldn't be necessary!] Restore the upper half of the ring heater to	in BSC	5 min	2+1	

Step	What	Where	Time	People	Tools
	its original condition.				
129	Reinstall face stops and set at 0.5 mm.	in BSC	10 min	2+1	hex keys
130	Finish routing ESD and OSEM wiring.	in BSC	20 min	2+1	
131	Suspend per Section TBD.	in BSC	??	2+1	
132	Drag wipe per Section 11.2.	in BSC	20 min	2+1	foil, lens tissue, methanol

11.1 Applying/removing First Contact

11.1.1 Applying

Step	What	Where	Time	People	Tools
1	See E070292-00.		3 hours	1	See E070292-00.

11.1.2 Removing

Step	What	Where	Time	People	Tools
79	Carefully shave the entire bevel with a sharp single-sided razor blade to remove traces of First Contact that may have spilled there off the face.		5 min	1	razor blade
80	With the edge of the razor blade leading, scrape from the bevel toward the face to prise up a corner of the First Contact on the face. The corner between the straight and curved sections is a particularly good place to start.		1 min	1	razor blade
81	Grab the prised-up corner with gloved fingers and carefully pull the whole sheet off the face, avoiding tears as much as possible.		1 min	1	

Step	What	Where	Time	People	Tools
82	If any small patches of First Contact remain, very carefully scrape them off with a razor blade and clean up the area with spectroscopic grade methanol and a lens tissue. (This should not happen if the First Contact was applied thickly enough originally.)		5 min	1	razor blade, methanol, lens tussue

11.2 Drag-wiping

Step	What	Where	Time	People	Tools
1	Pour a little spectroscopic grade methanol into a small foil boat or dish.		5 min		foil, methanol
2	Repeatedly, bend a sheet of lens tissue (3”x5” is good) in half without creasing it, dip the bend in the methanol and drag slowly across the optic. (Doug: This bend technique is particularly good for vertical surfaces.)		1 min		lens tissue
3	Work by strips, using a fresh sheet each time. If the lens tissue does not stick to the optic with surface tension, it is too dry. If it leaves streaks of liquid methanol behind (especially from the corners), it is too wet.		10 min		lens tissue