



LIGO Laboratory / LIGO Scientific Collaboration

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Advanced LIGO

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Review Report
Interferometer Sensing and Control
Final Design

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1 Executive Summary

The Interferometer Sensing and Control (ISC) Final Design Review (FDR) was held during the month of June, 2010. The requirements are described in [T070236-00](#), the final design can be found in [T1000298-v2](#) ("*Advanced LIGO Length Sensing and Control Final Design*"), [T0900511-v4](#) ("*Modeling of Alignment Sensing and Control for Advanced LIGO*"), [T0900385-v6](#) ("*The Advanced LIGO ETM Transmission Monitor*"), [T0900144-v4](#) ("*Arm Length Stabilization*"), [T1000276-v1](#) ("*Output Mode Cleaner*") and [T1000042-v2](#) ("*Tip-Tilt Mirror Mounts*"). An ISC block diagram can be found in [D1000653-v2](#), the list of ISC detectors in [T1000264-v2](#), the HAM1 isolation stack in [T1000310-v1](#), and a description of the high power beam dump is in [T1000300-v1](#). The cost estimate is detailed in [M1000119-v1](#), and the electronics manufacturing plans are outlined in [T1000320-v2](#). The review presentation can be found in [G1000638-v1](#).

We consider the ISC final review overall complete and recommend that the ISC team go forward with the production of the system. We consider the design of the length and alignment sensing and control, the ETM transmission monitor, the output mode cleaner, the tip-tilt mirrors, the design of the arm length stabilization scheme, and the lock acquisition technique in good condition. Great progress has been made in electronics design and mechanical drawings. However, we note that only about 50% of these designs have final drawings available. We consider this a serious schedule risk and strongly recommend that additional staff be added to help in drawing completion, manufacturing, testing and installation.

Follow-up reviews will be scheduled for the remaining scope to undergo its final review; these reviews may be undertaken via email if the basic designs remain unchanged. Revised person-power needs (in light of the recommendations below) must be established, taking into account the remaining design activities; if this falls on ops accounts, we also need to ensure availability of funds.

1.1 Procurement and Manufacturing

The one-arm test at Hanford and the Michelson test at Livingston set a very short time frame for procurement and manufacturing. Only a small subset of the total number of modules will be required in the short term; from a manufacturing point of view producing one or ten of the same module makes little difference. Furthermore, making multiple production runs will only aggravate the shortage of in-house resources. We support the plan of the ISC team to fully outsource these tasks and produce the necessary modules at the required final quantities for the three interferometers.

Action item: Select one or two electronics manufacturing services for outsourcing procurement and manufacturing. A close relationship with one or two manufacturing services will likely result in a more efficient working relationship.

Action item: Hire an engineer/technician to coordinate and oversee the manufacturing process.

1.2 Testing and Installation

The testing of modules requires a higher level of skills than procurement and manufacturing. It is therefore more difficult to outsource these activities and will require significant in-house resource. Furthermore, it is important that the expertise acquired during testing will be available at the sites

during installation and commissioning. A far better approach would hire this expertise in-house. For each module the same person would then be responsible for developing the test plan, perform and oversee the testing, leading the installation, verify its performance in the field and support early commissioning. The presently available resources for this task are completely inadequate.

Action item: The division between development, installation and commissioning had been a major point of inefficiency and consternation in initial LIGO. We strongly urge the ISC team to implement a solution for testing, installation and early commissioning support which guarantees continuity and clear responsibilities.

Action item: Hire 1 test engineer per interferometer at each site. This additional staffing is to be used for developing and implementing test plans, for installation, for quality assurance and for supporting early commissioning.

1.1 Rack Layout, Cable Plan and Slow Controls

Neither a final rack layout nor a cable plan was presented at the time of the review. We are particularly concerned by the lack of a rack layout, since this hinders progress in other areas such as the cable plan, rack procurement, power supplies, thermal load considerations and the slow controls. It is important to develop a cable plan months in advance of the actual installation so that cables can be procured through external manufacturers. Experience in initial LIGO has shown that a partially worked out cable plan will result in tying up a significant amount of in-house resources at the time of installation. Hooking up the slow controls system, setting up the software, testing each individual channel and supporting the development of the user interface requires a non-trivial amount of resources.

Action item: Complete the rack layout with high priority.

Action item: Develop a cable plan so that procurement can start by the end of 2010.

Action item: Hire the equivalent of 0.5 FTE of additional engineer/technician support at each site to develop and oversee both the cabling as well as the slow controls system.

1.2 Procurement of Optics and Opto-mechanical Components

Recent experience has shown that the procurement of super polished optics can take up to six months. Because most of the optics will be custom orders, significant cost savings can be realized in combining orders where possible. We encourage the ISC team to develop a procurement plan for the optics and opto-mechanical components, so the orders can be placed by the fall of 2010. We also support combining orders with other subsystems where it makes sense.

Action item: Develop an ISC wide procurement plan for optics and opto-mechanical components. Investigate the possibility of sharing orders with other subsystems.

1.3 Resolution to the Action Items of the Preliminary Design

Action item: Make a decision whether mode 0 will be used in the first phase of commissioning, or not. And if so, at what point would we switch over?

This question will be addressed during early commissioning at the LIGO Livingston Observatory. There will be a blank signal recycling mirror which can be used to switch to mode 0 if desired.

Action item: Investigate the possibility of a more robust mode of operation for the alignment sensing and control, which can serve as a stepping stone to commission high power operations and shorten the overall commissioning time. We feel that the new near and far field quadrant photodetectors in the end stations, cameras looking at the ITM and ETM, as well as wavefront sensors on the green beams still have untapped potential.

A robust mode with a diagonal sensing matrix has been added to the final design.

Action item: Engage the LSC calibration group to develop a realistic plan on how to reach a 1% amplitude and phase calibration.

We recommend that the ISC team and the calibration team look at the possibility to use the rear injection capability to directly measure test mass displacement. We expect significant progress by the end of the year.

Action item: More resources have to be allocated to program, test and validate crucial software pieces. In particular, the scrutiny and documentation of software paths which are part of the gravitational wave signal readout have to be on a similar level as currently practiced by the data analysis groups. Algorithms have to be analyzed for validity, performance and limitations. All testing has to be documented.

Additional resources have been added to the data acquisition team and progress has been made in software development as well as testing. However, no specific ISC related issues have been identified or addressed. At the end this may not be the most urgent problem, but the committee feels it is worthwhile to consider additional resources to support software development in the early commissioning effort.

2 Technical Scope

2.1 Scope

The Interferometer Sensing and Controls system is responsible for bringing the optical resonators into a mode of operation suitable for detecting gravitational waves. This includes the longitudinal and angular degrees-of-freedom of the input mode cleaner, the main interferometer and the output mode cleaner. It includes photodetectors, demodulation electronics, analog filtering, A/D converters and the computer hardware and software. The ISC system interfaces with the Suspension (SUS) Subsystem for the actuation on the optics, and with the Pre-Stabilized Laser (PSL) for actuation on the laser frequency. The modulation scheme is implemented by Input Optics (IO), according to the requirements of the ISC system.

2.2 Charge to the Review Committee

The charge to the review committee is outlined in M050220-09.

1. With regard to requirements:

- a) Review and approve changes to the design requirements.

2. With regard to the preliminary design:

- a) Determine if all action items of the preliminary design have been addressed.

3. With regard to the final design:

- a) Evaluate the final design of the ISC to determine if it is sufficiently advanced to qualify for a final design,
- b) review the final engineering drawings,
- c) review the procurement and manufacturing plan,
- d) review the QA and testing plan,
- e) review the schedule and staffing plan,
- f) advise whether the project cost and schedule appears appropriate, and
- g) advise whether there are any newly-perceived risks in meeting the requirements.

4. With regard to the installation:

- a) Advise on the installation plan and early commissioning activities.

The committee should develop a set of actions as a result of the review, and should follow up on the completion of the actions as part of the review process.

2.3 Review Checklist

- A. Final requirements – any changes or refinements from PDR?
no change.
- B. Resolutions of action items from PDR
see previous section.
- C. Subsystem block and functional diagrams
done.
- D. Drawing package (assembly drawings and majority of remaining drawings)
with exceptions.
- E. Final parts lists
Parts lists exist for nearly all of the in-vacuum detection chains (Trans Mon, HAMI, etc). Rack layouts show electronics module. The reviewed modules have parts lists.
- F. Final specifications
done.
- G. Final interface control documents
done.
- H. Relevant RODA changes and actions completed
done.
- I. Signed Hazard Analysis
not required.
- J. Final Failure Modes and Effects Analysis
photodetector shutter.
- K. Risk Registry items discussed
There are no items in the risk registry marked as ISC.
- L. Design analysis and engineering test data
mostly done.
- M. Software detailed design
This is part of the DAQ system. See also previous section.
- N. Final approach to safety and use issues
done.
- O. Production plans
only partially existing.
- P. Plans for acquisition of parts, components, materials needed for fabrication

only partially existing.

Q. Installation plans and procedures

Schedules in accordance with the LLO Michelson test and the LHO one-arm test.

R. Final hardware test plans

TBD.

S. Final software test plans

none.

T. Cost compatibility with cost book

Costs are re-estimated in M1000119. Current cost estimate (equipment) is about \$300k, or about 8%, above cost book.

Note: The costs will increase if the recommendations for additional personnel are adopted.

U. Fabrication, installation and test schedule

only partially existing.

V. Lessons learned documented, circulated

part of the design documentation.

W. Problems and concerns

Current resources not sufficient for procurement, manufacturing, testing and installation. The schedule risk is high.

3 Review Comments and Questions

Here is a collection of questions and answers which were investigated during the review process.

Diode damage. What is the spec for acceptable power on the diodes, considering that we have found that low levels of damage increase jitter coupling. Is the required shutter performance reasonable?

The damage limit for the diodes is not well known. Looking at the history, it looks like we had some diode damage during S4; there we had 3 W into the interferometer, and some of the shutters probably weren't working right, so that the full output pulse energy, or close to it, would have incident on the AS port diodes. This would have been about 1 J total, or 0.25 J per diode. On the other hand we didn't notice any diode damage when we had 1 W input. As stated in T1000294, we are using an energy threshold of 100 mJ total for aLIGO for setting the shutter time scale, which appears to be a safe level (50 mJ per diode). In the meantime, a program of diode damage testing has recently been started at Caltech.

Cameras. For which diodes (if any) are in-vacuum cameras being planned?

We are not planning on implementing cameras in-vacuum. We will be looking into what views of diodes we can get through chamber viewports.

Fringe wrapping and baffling. It seems likely that the microseism will cause some chamber walls to move by roughly a micron relative to the in-vacuum ISC tables. It also seems likely that the walls will be lit up with large angle scattering from core optics. Is there danger of fringe wrapping up-conversion from this large angle scattering recombining at the ISC tables? Should the tables be enclosed to baffle them? Light scattered from core optics directly onto the tables may also be a source of non up-converted scatter noise.

We haven't tried to evaluate this quantitatively; seems like it would be hard to get any reliable results. On the other hand, it is certainly worth taking care to limit the field of view of the critical in-vacuum photodiodes. In general the photodiode mounts are designed so that baffling tubes can be mounted to them.

Fringe wrapping. Are there plans to dump all ISC table beam spots on the tables themselves?

Yes.

Electronics testing. Is there a plan to measure acoustic and magnetic coupling factors for the demodulator boards, and other key electronics, over the adLIGO band?

We did this for the demodulator boards. This info can be found in the demodulator design documentation on the wiki (this design was previously reviewed). We haven't measured coupling factors for any other electronics at this point, but we will keep the issue in mind.

Tip tilts. How much has the magnetic coupling of the tip tilt mirrors been reduced? Are there plans for a 60 Hz feed forward system?

Measurements of the coupling are being done now, but no definitive results yet. The coupling should be reduced by a combination of removing the 5th magnet on the optic ring holder, and reducing the size of the 4 actuator magnets. We are considering reducing the magnet size to 2 mm

diameter x 3 mm long (compared to 5 mm x 10 mm). These smaller magnets would give ± 10 mrad of DC alignment range, which sounds sufficient. Their volume is smaller than the current magnets by a factor of 20, so we would expect at least a factor of 20 reduction in the coupling. Feed-forward cancellation could always be implemented if that is not enough.

Tip tilts. Is the plan to have a position damping servo for the tip tilts? We have found that the vibration isolation of the tip tilt mirrors is very important because of jitter coupling. It is difficult to adjust eddy current damping, and over-damping can make the isolation less effective. Is there a scheme for making sure that the vertical motion damping magnets don't over-damp?

Yes, the tip-tilts will all have BOSEMs so they can be actively damped in position, pitch and yaw. The inherent eddy-current damping will be much smaller with the smaller magnets. The vertical and roll eddy-current damping implemented on the blades is adjustable. The side and vertical damping on the optic ring is also adjustable. We see no reason not to make these modes all fairly lightly damped (say, Q of 10-40).

Seismic spectra. Only LLO seismic spectra were used for ASC planning. At LHO EY the 95% seismic level is a factor of about 3 worse than at any of the LLO end stations in the 4-10 Hz range due to route 240 truck traffic. Is there enough leeway to allow for these variations between sites and buildings? Also, why use 90% instead of 99% or 95%? Seismic transients in the 95% percentile can happen every hour (e.g. trucks).

The LLO 90% seismic contours are the highest percentage contours that have been generated; that is why we used them. We could continue to do more and more modeling with different inputs, but we don't think that is very profitable at this stage.

Seismic spectra for in-vacuum tables. Because there are fewer passive isolation layers, we will have much more vibrational noise on the in-vacuum tables in advanced LIGO than in initial LIGO. Have realistic estimates of noise above 100 Hz been used when this noise might affect performance?

Probably we need more clarification of this question, because we don't really understand what is being asked about. Clearly the ISC detection chains for the ETM transmission, REFL, and POP paths will have much more isolation than in initial LIGO, since they have no vibration isolation now. For the AS path, the ISI table noise will be essentially the same, but the isolation of the tip-tilt stages should be improved.

Damping. Are the planned in-vacuum ISC tables damped like the external tables? Is there an in-vacuum damping system available so that components may be damped?

No (the damping in the external, commercial optical tables is not vacuum compatible). We did not have any plans to damp in-vacuum components, like kinematic mirror mounts. Any suggestions on how this could be done?

RF. Has the 9 and 45 MHz RF background at LLO been studied?

Yes, there is some data on this posted to the [wiki](#).

Some of the LVEA racks look like they have a fairly high board density. What kind of cooling is planned for electronics in the LVEA ISC racks (any fans)?

No fans. There has been some testing of this heat issue at Caltech. This led to the basic approach of loading up the racks with one or more 1U gaps between modules, and using perforated top panels for the chassis.

Where are the isolated ISC racks at the end stations going (e.g. entry bay)?

Not clear what you mean by 'isolated' racks. But what we call remote racks will go into the entry bay – i.e., the room where LI currently has its end station electronics.

Whitening chassis: it is not unlikely that there will be always a whitening stage saturating, if the ADC range is used to at least 10%. Saturation depends also on frequency content. This is not so nice, as saturating OpAmps can make noise on the power lines, but also on their inputs. At a very least measure to reduce these influences, the non-inv. inputs of the whitening stages should be isolated by resistors. Also: The resistors help to balance the DC offset of the whitening stages. AD829 has pretty high bias current, but it is mainly common to both inputs, so can be reduced if the input impedances are balanced. Otherwise the offset can be up to 50-100mV, which would be switched in, of the stage is engaged. This is not a good situation.

From this and other review comments, the following changes have been made to the whitening filter:

- 1. Increased differential receiver resistor values by a factor of 3,*
- 2. Corrected typo in differential receiver values as pointed out by Hartmut*
- 3. Incorporated a resistor in series with the positive input on switched stages to address the above saturation input impedance issue.*

On one image of a front panel of a common-mode board I saw that the LEMO connectors have a rather small gap from their shield to the front panel. Why not make the holes bigger? It doesn't cost much and can avoid so much pain with ground loops.

Sure; in fact we may instead put in a plastic shoulder washer between the connector and the panel hole.

What is the state of the OMC longitudinal noise estimation? Is the coupling expected to be different from eLIGO? Is there an idea of the noise of the multi-stack PZT? (We are trying to measure in GEO).

The story is not completely clear, but basically OMC length noise seems to be below the readout noise in eLIGO, by a factor of a few or more. There are a bunch of resonant features in the OMC length noise measurement above a couple of kHz that are probably mechanical resonances of the OMC, but their level of excitation seems to be above thermal, and it is not yet understood why (in any case the coupling puts them below the GW readout noise). We don't expect the coupling to be any different in aLIGO, but hopefully there will be fewer of these resonances in the GW band with the thicker tombstones that we are planning. We don't yet know the noise of the longer throw PZT, but are trying to measure it.

Is there a final Interface Control Document.

There is an ICD for the Transmission Monitor (between the AOS suspension and ISC): E1000222. The other significant interfaces are between ISC and IO, regarding beam delivery from IO to ISC. So far this has been documented in viewgraphs, but should be written into an ICD.

Is there a Software detailed design?

No.

Has the final approach to Safety and Use Issues decided upon and documented.

Don't know what is meant by Use Issues. We haven't identified any significant safety issues, other than the standard procedures for working with laser beams.

Have all of the lessons learned been documented and circulated?

We went over 'lessons learned' at the ISC PDR; refer to that documentation if interested. But no, surely not all have been documented and circulated.

Are all Problems and Concerns documented?

The only truthful answer can be no—there are always problems and concerns that aren't documented, typically because people are working on solving them rather than documenting them.

ISC Equipment Block Diagram (D1000653-v1)

- In section 3.2 a document number T90238 should be T970238. In section 3.3 it is said that “There is a product called Dyneon FC 2176 that presumably is the same as Fluorel-2176.” Is it known that they are the same material since processing per E970130 might not work if the material is different.

Hasn't been checked yet; perhaps we can get help from aLIGO QA to do this.

Advanced LIGO length Sensing and Control Final Design (T1000298-T)

- Table 2 of this document does not agree with Table 1 of the Optical Layout and Parameters for the Advanced LIGO Cavities T-0900043-10 for the distances from the PRC to the beamsplitter and the SLC to the beam splitter for either the non-folded or the folded IFO.

We're confused: Table 2 of T1000298 does not even mention these distances (assuming you mean PRM/SRM – PRC is not an optic); the PRC and SRC cavity lengths do agree. Please clarify question.

- Figures 9 through 16 show 70 line graphs. How was the code checked that was used to compute these curves.

The lowest level of the code – Optickle – has been fairly extensively tested and checked against other codes and experiment over the years. Beyond that, for looptickle and the actual curve-generating scripts, this was all done by Stefan B, so we're relying on his own self-checking of his work (no guarantee that there aren't errors).

- In tables 3 and 4 how was $l+m \leq 6$ selected.

This seemed to be a pretty conservative upper limit on the HOM that could be problematic. Not only are higher order modes less likely to be excited, they also have a lot more loss in the arm cavities.

- Optical and looptickal are plane wave models does the finite transverse extent of the optical modes effect the quantum noise.

We don't see how; the OMC selects out just the fundamental mode.

Length Sensing and Control: Design document: T1000298.

- p 1. In the section states of operation there are three states, so far only state 1 and 3 are described. What about state 2, how is the transition state handled?

The transitioning state will be handled basically as it is now; i.e., with a script (set of scripts) that transition from the acquired state to the low-noise state.

- p 2. In the section modes of operation, ‘mode 0’ is listed but is actually not a real operational mode. Why is it listed, as this mode is only a commissioning mode in the path to the installation of the SRM.

It could be a real operational mode (didn't we discuss this at the review meeting?).

Note: The narrow-band mode must be considered (and carried) as a potential future operational mode as it is a deliverable for aLIGO. While no detailed design is needed, compatibility of the ISC infrastructure with the narrow-band mode should be addressed.

- p 2. On what basis is the choice for serial modulation made, technical/implementation? Why and when would you want to retrofit a Mach-Zehnder setup?

Serial modulation is chosen because it is simpler, and as App B shows, produces an acceptable sensing matrix, not very different than that with the MZ. We have no idea when we might want to retrofit a MZ; that depends on if and when any problems are found with serial modulation.

- Table 3 (p. 7) highlights the sideband frequency away from arm cavity resonance, for example the 1209th upper high sideband resonance is 975 Hz away from cavity resonance. How likely is it that this resonance will pop up?

Perhaps you're misinterpreting the table. This particular line says that any 4th spatial-order mode content of the +45 MHz sideband will be 975 Hz away from arm cavity resonance. In any case it certainly does not seem likely that this will 'pop up', but we have not attempted to quantify the likelihood. The point of this table was more to look for any modes that might be within a line width or two of an arm cavity resonance.

- p. 11/12. How is the DARM offset measured? Is this ‘set’ or is the offset tuned until there is 100mW of power on the AS_DC diodes?

In practice it will be set by optimizing the strain sensitivity.

- p 13. Section 2.4, How much input power is assumed (in the IMC and IFO) for the ‘Optical Port Power’ tables on page 13.

125 W incident on the PRM; the same, or maybe slightly more, incident on the IMC.

- How are the 4xf1 frequencies (higher order modes of the f1 frequency), being distinguish from the f2-f1 frequency?

*Assuming you mean higher harmonics (rather than higher order modes), they are not distinguished; both frequencies are simply part of the simulation (obviously the 4*f1 components is very small).*

- p 15. In the sensing matrixes the REFL IM signal for the SRCL length seems to be dominated by the PRCL. How is this mitigated?

The sensing matrix will have to be diagonalized in software (this is how it was done in the simulation; note: such SW diagonalization has been done for alignment control in eLIGO and in the 40m)

- p 16. Section 3.3, With the modeling of the seismic noise only the Quad and ISI are incorporated. How much would the performance change when including the Triple and HAM suspensions?

Good question. We recognize that we are going to have to include HAM ISI and triple suspensions in the LSC model, and see what we get (our original LSC modeler, Stefan B, has moved onto other things, so we need to find someone new to further this modeling).

- Oscillator amplitude noise seems to limit a number of loops, see fig 9, and fig 11. Can anything be done?

This is true for the NS/NS tuning case, but not really for the zero-detuned case, which is our baseline mode of operation. The NS/NS mode may well be of interest at some point in the future, and is a deliverable for aLIGO. We probably meet requirements with no improvement, but we have a design for a low noise EOM driver under development—albeit it won't be reviewed in the short term.

- p 26. How realistic is it to make the correction path accurate to 1%?

Currently we do get correction 1% routinely, and Virgo typically gets a factor of 10 better.

- p 29. What is the strategy for running the interferometer without an SRM? For how long will it be running, what needs to be achieved before the SRM will be installed? Will the SRM+SUS not be installed or being replaced by a blank optic? This may not be in the remit of the ISC team.

Current plan is to begin operating with the SRM with the vertex interferometer at LLO. This experience will inform whether we want to keep it in with the full interferometer. 40m experience with full interferometer control will also come into play. The SRM+SUS will be installed in any case, potentially with a blank optic.

- Overall outline/flowchart of lock acquisition procedure?

The outline is in T1000264: description in Sec 3 and sequence shown in Fig 5.

Alignment Sensing and Control: Design document: T0900511

- What is the role of the optical levers in the ASC scheme?

Currently they have no role in the scheme. They may be used in practice as alignment monitors and for some damping.

- Are there any plans for time domain simulation?

No. We don't envision any need.

- How do signals vary as a function of SR tuning? Will a similar scheme be effective for all tunings?

This hasn't been studied.

- p 3 What happens if the thermal lens in aLIGO is also not perfectly compensated?

The mode matching will suffer (can be compensated by increasing the injected power). Distortion effects on the ASC signals have not been studied (don't really have the wherewithal to do so).

- Will aLIGO have any beam centering servos?

Yes.

- Just a note. Should the $\{-1\}$ not go with the first matrix in (3.5) ?

Yes, should be corrected.

- Would it be beneficial to apply control forces higher than the penultimate mass?

Certainly long term drifts (not in the model) can be applied to the upper intermediate mass.

- Can we safely assume that the difference in restoring force between pitch and yaw is negligible?

Yes (we looked at it; they're close enough).

- Has any study been made regarding the use of the green ALS beams for alignment? Might be useful even if just for acquisition mode (since all signals are dominated by arm motion).

No study, but this is one of the goals of the single arm testing on H2.

- Can PR2/SR2 be sensed and controlled if necessary?

We can't distinguish between PR2/SR2 and PR3/SR3 with global signals.

- p 51. When will control filters that can operate at different powers be looked at? Will commissioning trips be required each time power is increased?

The document shows filters for 25 W and 125 W already. Filters that can operate over a wide power range is clearly a long term task. Commissioning work will certainly be needed for power increases.

- How successful was local damping of the suspensions in iLIGO? Are we confident that it will work in aLIGO?

Local damping has always worked in iLIGO – we're about as confident as one could get.

- p 56. Will feed forward cancellation of longitudinal-pitch coupling be explored in aLIGO?

This is already in the alignment control modeling (sec C.2.1), so yes it will be explored (i.e., made to work).

- p 64. Should waist be removed from first equation?

Yes (typo).

ETM Transmission Monitor: Technical Design Document T0900384; Assembly D1000484; High power beam dump T1000300.

- p 2. There is a reference to the viewport interface, but none is listed.

Right. There are requirements and preliminary design documents for the viewports (T1000022 and T1000023, respectively); these are what should be cited here.

- p 2. There is reference to viewports in fig 1, but none are visible. It is mentioned that the green beam is directed through the middle viewport, but fig 2 shows that it goes through the most right VP. Which viewports are used?

Each transmon table installation is slightly different: H1 vs. H2 have different beam centerlines, X end and Y end are mirror images from each other. The simplest layout from the transmon point of view is to have the two green beams use the center viewport, IR beam uses the +X, +Y viewport. This has the largest impact on the in-air ALS table, and can be changed to suit their needs.

- p 2. Are the green QPDs on the transmon table used as a reference or as an aid for the alignment of the green beam into the cavity? The green beam has wavefront sensors on the in-air table.

We expect to use the QPDs to align the green beam to the cavity. The WFS are planned more as a diagnostic. But all this could change with the H2 arm cavity testing.

- p 3. Mention of a BRT, which I presume stands for Beam Reducing Telescope. Also, the references to the Gouy telescope (and QPD positioning) is that for the IR, green or both beams?

Re: BRT, correct. The Gouy telescope references refer to both the IR and green telescopes. They will be similar, though corrected slightly for the different colors.

- p 4, just above eq 3, ..the cavity length must satisfy ... I presume should be ‘...the optic separation must satisfy...’

Right, or ‘the telescope length must satisfy...’

- p 5. What is the appropriate output beam & distance for the Gouy telescope?

As written up in T0900385, the Gouy telescope output has a waist of about 250 microns that must be spaced at least Z_R from the second lens. 250 microns is a compromise between a small spot size at the QPD (350 microns) and keeping the QPD separation short at the output ($2 \times Z_R = 36 \text{ cm}$).

- p 6. What is the Matlab ALM package, is there a reference?

[ALM](#): a la mode; a set of mode-matching functions written by Nic Smith.

- p 6. Section 5, are the QPD signals normalized to both the waist and divergence angle?

Yes.

- p7/8, fig 6, the QPD signals below 0.6 Hz is dominated by the table motion. Then in fig 7, the ISI angular noise will dominate the QPD signals. Does this become a problem when using the QPDs? Will the beam drift of the 3mm diameter QPDs?

We don't see how the beam could drift off the QPDs (they would have to move by a beam diameter or more on the ETM to do that).

- p 7. Why is the required telescope motion only 5x less than the smallest of the cavity motion?

Factor of 5 gives plenty of margin

- p 10. The BRT length tolerance is set to <100 micron, is this realistic?

Yes (the AOS folks are planning how to do this, using a Shack Hartman sensor).

- p 11. The in-vacuum temperature tolerance is set to <1.2C, is this achievable over long time scales? What is the current long term in vacuum temperature stability?

It doesn't seem too crazy, but we haven't studied the long term in-vacuum stability

- p 12. With the predicted change of path length due to the ETM thermal lensing and the QPD matrix elements should be measured after a thermal equilibrium. Does this require dynamic matrix elements for the various modes of operations? What if the path length change is too much? Does this require a vacuum incursion?

*Dynamic matrix elements aren't required. However, the exact transmon matrix **may** depend on the IFO buildup, etc, but only for the best science mode angle to length decoupling. If so, then the different power levels will load the appropriate matrix, as we currently do for WFS, TCS, etc. The spec is written so that we won't need an incursion. If we don't make spec...*

- 'Transmission Monitor Telescope and Suspension (TMS), Preliminary Design Document', the optics mounted on the TMS platform seems very delicate. Can the beam height be reduced? Also, the periscope for the Hartmann beam seems quite tall. Does this introduce unwanted resonances?

see below.

- What is the beam height on the transmon table?

The beam height is 4 inches, which is the standard we have used on ISC tables in iLIGO and aLIGO. The mounting is also done as in iLIGO, with 3/4" posts, etc. And note that all of this is on a well-isolated platform. We will look at the Hartmann beam periscope with K. Mairland; it can probably be reinforced if necessary.

Lock Acquisition: Design document: T1000294

- Has the ALS system been incorporated into the lock acquisition modeling?

Yes, it is assumed that the ALS will perform as described in the note.

Arm Length Stabilization: Design document: T0900144

- p 12. What will the separation of the two green beams (X arm transmitted and Y arm transmitted) be on the PSL table?

The IO folks have looked at this, given the tolerances on the wedges. The separation will be a few beam diameters, plus or minus a couple beam diameters.

- p 13. The local oscillator noise for vertex beat note measurements is only 3x below the noise. Is this enough?

Yes, factor of 3 seems like enough margin, but we're still looking at whether these calculations are correct.

- p 15. Has the handover from ALS to global length sensing and control been studied?

It hasn't been simulated. But it is because of the handover question that we are adopting the common mode control scheme (so in some sense, yes).

- Can the green beams be left on during science mode e.g. for arm alignment?

We will be able to try that

- Feedback modeling to the quad only takes the test mass and the penultimate mass into consideration. Would feedback to all stages further reduce the signal levels to the penultimate mass and the test mass?

Certainly long time scale control can be applied to the upper intermediate mass, if desirable.

- Can the green beam be used for arm length calibrations?

Potentially, though this isn't being investigated at this time.

Output Mode Cleaner: Design document: T1000276

- Given the problems seen in eLIGO, how will the input beam be aligned to the OMC in aLIGO?

Probably the same way it currently is: drumhead alignment. The stable recycling cavities should ameliorate the junk-light problems we had with eLIGO. Only a spectrum can tell definitively. We will include all of the known sensors and techniques: QPD, WFS, dither, and drumhead and will use whichever works best

- p 1. Will a long throw PZT introduce any alignment errors over its travel?

These new PZTs are being tested for just that by Valera at LLO; no definitive results yet.

- p 1. I assume the exposure to UV necessary to cure the epoxy has no consequences for the transmissive optics.

That's right; the UV emission is short, and not directed at a coated optic.

- p 2. Why is a power law assumed for the junk light in HOMs?

It's just a guess – we wanted some sort of model where the power went down as the mode index went up.

- p 5. Will the delayed construction (only after AS port spectrum has been measured) of the OMC impact the schedule of the project.

No; we plan on re-using the existing OMCs at the start of aLIGO.

- Why was the design of the aLIGO OMC constrained by the proportions of the eLIGO item? Was there a requirement to use the eLIGO suspension?

It wasn't really constrained; we could have made new suspensions and/or some entirely new design if we thought we needed to. But we didn't; we concluded that the basic eLIGO design and its suspension would work for aLIGO.

- What measures are taken to mitigate scattered light in the OMC?

There is limited deployment of black glass, particularly for the DCPD reflected beams. The black glass is either mounted directly to the OMC breadboard or to the HAM table. There are no current plans for extensive baffling at other locations on the OMC. One obvious improvement is to baffle the OMC QPDs in order to limit the confusion during initial alignments. Other baffling will be difficult.

Tip-Tilt Mirror Mounts: Design document T1000042; Assembly drawing D1001396.

- Are the TT structure resonances bad for the HAM-ISI (p. 12)?

No; they are higher frequency than what is worrisome for ISI control (below 150 Hz or so), and their mass is relatively small so they don't couple much to ISI dynamics.

- What are the quality factors of the side and vertical modes?

See previous answer.

- Are the TT being considered for shuttering actions? If not, are the BOSEMs still required?

No; a separate fast shutter will be developed. We still want BOSEMs (could be aOSEMs) for pointing control, active damping, and dithering. The magnets will be much smaller to reduce B-field coupling (see above).

- Are the eigenmodes of the TT problematic for the HMA tables?

Experience with eLIGO says no, nor would we expect any problems given the relatively small mass of the TT mirror.