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# Remarks at the PPARC Review of the UK Contribution to an Advanced LIGO

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14 October 2002



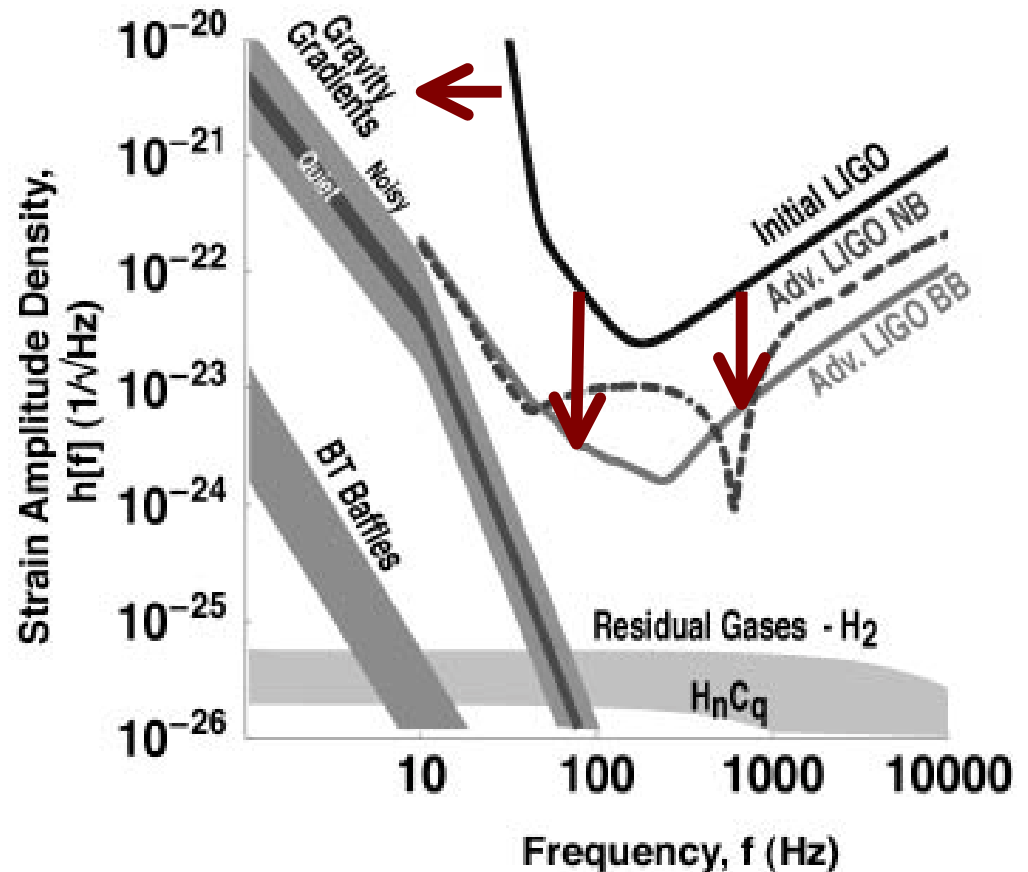
# Topics

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- LIGO Plans for Improving Sensitivity on the Initial Interferometers
- Working Allowance
- Spares Philosophy

# Present, Advanced, Future limits to sensitivity

- Advanced LIGO
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
  - » Initial → Advanced: factor <1000 in rate
- Facility limits
  - » Gravity gradients
  - » Residual gas (scattered light)
- Beyond Adv LIGO
  - » Seismic noise: Newtonian background suppression
  - » Thermal noise: cooling of test masses
  - » Quantum noise: quantum non-demolition





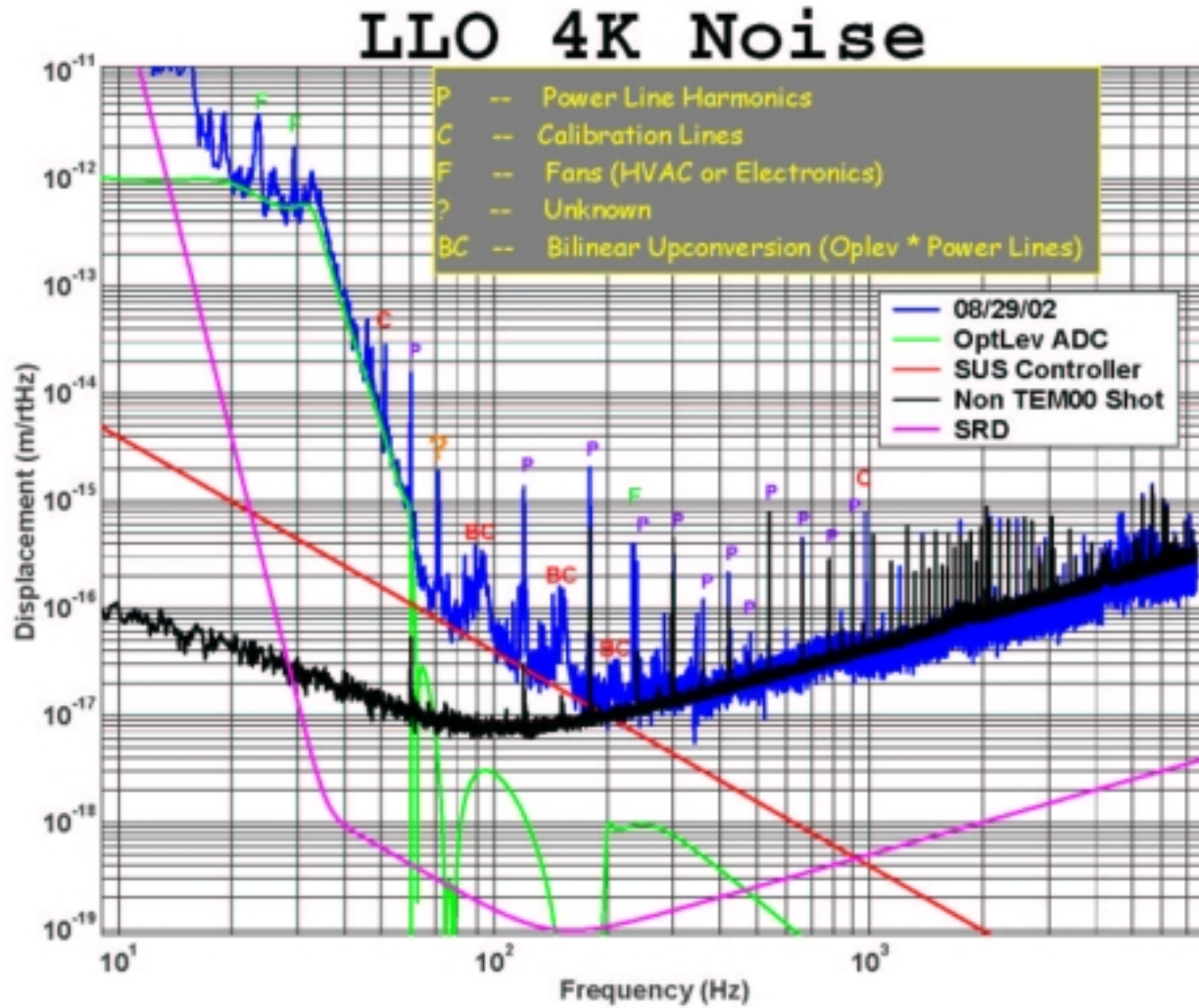
# First LIGO Science Run (S1)

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- August 23 - September 9, 2002 (~400 hours)
- Three LIGO interferometers, plus GEO (Europe)
- Steady improvement in sensitivity continues
  - » Range for binary neutron inspiral ~ 40-100 kpc
- “Glitch” rate (non-gaussian noise) is reduced compared with previous runs
- Hardware reliability good for this stage in the commissioning
- Analysis results (upper limits for several types of sources) expected by early 2003



# Understanding the Limiting Noise Sources





# S1 Noise Breakdown

- LOCAL DAMPING - Assumes a sensor noise level  $10^{-10}$  m/rtHz from the OSEM readback of the position degrees of freedom. The filtering is less aggressive than ultimately intended.
- OPTICAL LEVER - The Pentek ADC's which digitize the optical lever readouts have  $\sim 30$  uV/rtHz of input noise. This level translates to  $\sim 200$  picoradians/rtHz of sensing noise. Through aggressive low frequency filtering, the linear coupling of this noise to the gravity wave channel was removed above 60 Hz, but through a bilinear coupling process the big mountain of optical lever noise at 30 Hz was upconverted into the broad bumps seen at 90, 150, and 210 Hz.
- SUS THERMAL - peaks are consistent with thermally excited suspension wires having Q's of  $\sim 100,000$  which produces vibrations of the test mass slightly exceeding the Science Requirements curve.
- COIL DRIVER - The old (and now retired) analog SUS controller we had for the large optics during S1 had 150 nV/rtHz of excess noise  $\sim 5 \times 10^{-17}$  m/rtHz @ 100 Hz.
- DARK + SHOT - The (dark) thermal noise in the RF PD's resonant circuit contributes at  $\sim$  the same level to the sensing noise as the shot noise from the non-TEM00 mode light. The factor of 2 fluctuations in our sensitivity during the run were due entirely to the fluctuating alignment state of the IFO. IFO sensitivity above 200 Hz is expected when the wavefront sensor system is fully commissioned (will allow a larger fraction of the Anti-Symmetric port light to be detected)
- SRD – Science Requirements Document: target sensitivity for initial LIGO



# Current (S1) Noise Sources

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different according to the interferometer, but taking LLO as an example:

- Up to ~60 Hz, limited by Optical Lever sensing noise. To be addressed with
  - » wavefront sensing; major next step in commissioning
  - » more aggressive low-pass filtering
- 60-200 Hz, limited by the suspension electronics (output amplifier noise). Addressed by:
  - » changing to a 2nd generation suspension controller (allowing lower noise and more aggressive filtering)
  - » through re-allocation of authority (see pre-isolator below)
- 200 Hz and above: Photon shot noise
  - » The present limit is for less than 1 mA (1 mW) of sensed intensity, due lack of wavefront sensing, because of variations in interferometer contrast. Neutral density filters in place to protect diodes from high-power fluctuations.
  - » Input power and optical efficiencies are already at levels comparable to the final values



# Plans for Improvements

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- Paced by further science runs
  - » S2 is likely mid-Feb to mid-April
  - » S3 will start in Fall 2003.
- Between now and S2:
  - » Installation of Second generation suspension electronics, to lower noise, allow tuning of transfer functions, improve reliability
    - Already installed and tested on LHO 4k
    - Now being propagated to LHO 2k and LLO 4k
  - » Installation and tuneup of the Wavefront Sensing, to control all angular degrees of freedom
  - » Improved intensity stabilization
  - » Incremental improvements in electronics and control code



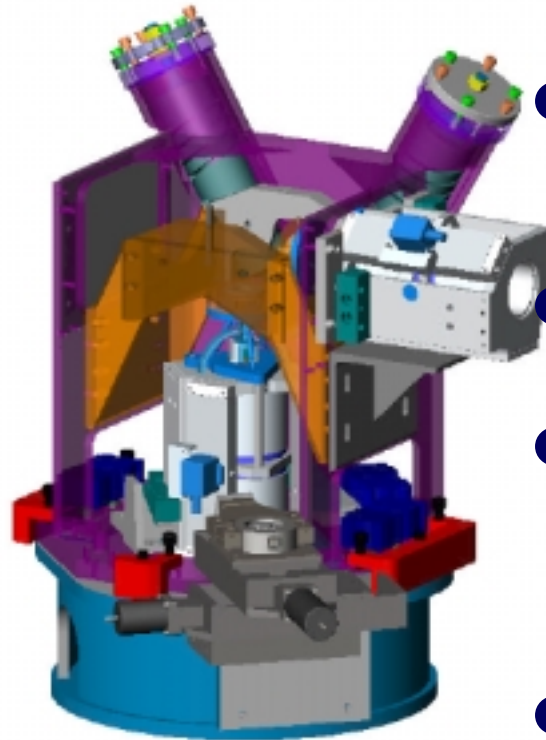
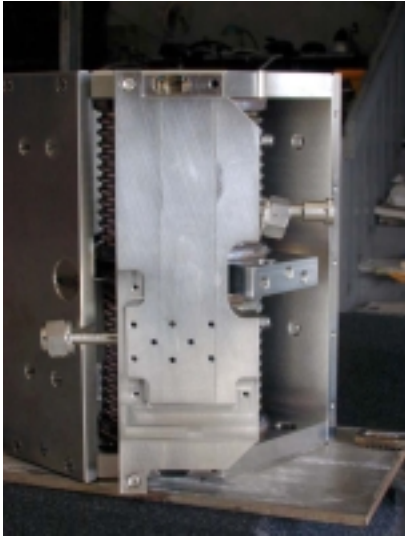


# Plans for Improvements (continued)

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- Between S2 and S3:
  - » Installation of a Seismic Pre-Isolator in LLO and LHO
  - » In LLO, an aggressive active isolation system to address excess low-frequency (0.1 - 10 Hz) noise due to logging activity around the observatory. Presently being prototyped on Campuses. This will allow a much-increased duty cycle, and allow actuator authority to be taken from suspension actuators.
  - » At LHO (which is quieter than LLO), installation of additional sensors and controls on existing actuators to allow more actuator authority to be taken from the suspension -- principally to lower noise and to allow operation in windy times.
  - » Refitting of electronics to reduce RFI
  - » improved DACs
  - » Second generation analog control boards
- Goal: to be 'within a stone's throw' of the final sensitivity for the S3 run in all 3 interferometers.

# Hydraulic External Pre-Isolators (HEPI)

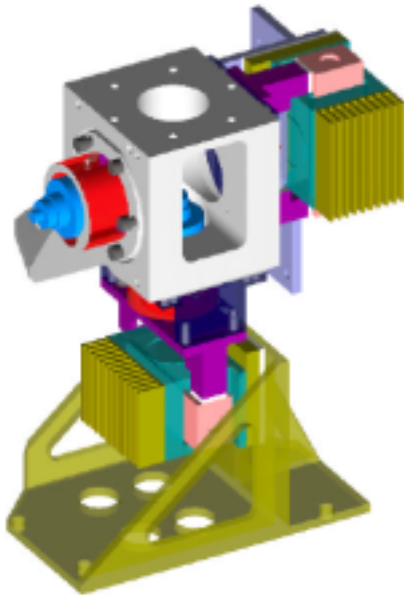


- Working fluid is low-viscosity mineral oil
- Bellows hydraulic pistons apply force without sliding friction, moving seals
- Laminar-flow differential valves control forces
- Stabilized “power supply” is remote hydraulic pump with fluid-equivalent “RC” pressure filtering
- Technology adapted from precision machine tool applications

K. Mason, MIT

# MEPI Installed on HAM13

- Uses commercial voice-coil actuator
- 'Pin-compatible' mechanically
- Simpler electronics
- 'Soft' mechanical back impedance



G020470-02-D



*UK Contribution to an Advanced LIGO*



# Working Allowance: Cost Estimate - Risk Analysis\*

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## “Working Allowance “

- » is often misunderstood in Washington DC re scientific projects
- » It is not possible to complete a project on plan without appropriate working allowance resources

\*from a talk by Gary Sanders: [http://www.ligo.caltech.edu/~sanders/Introductory\\_Lecture\\_files/frame.htm](http://www.ligo.caltech.edu/~sanders/Introductory_Lecture_files/frame.htm)  
also defined in the LIGO Cost Estimating Plan: <http://www.ligo.caltech.edu/docs/M/M990310-04.pdf>



# Working Allowance: Cost Estimate - Risk Analysis

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- Estimate for each item should be the expected cost of the item excluding unusual or adverse risks
- For each item, separately estimate the technical, cost and schedule risks for that item. Use a standardized and disciplined method for all items and all estimators. Develop an estimate of an amount of money to be held in reserve to deal with the average of all risks. Not all risks will actually take place during the Project. This amount of money is the “working allowance”.
- Primitive method - bulk percentage rule of thumb
- Better method - Standard Risk Factor/Percentage
- Best method – cost of point design response to each risk – not usually practical



# Cost Estimate – Working Allowance %

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**Working Allowance (%) = Technical risk factor x Technical risk %  
+ Cost risk factor x Cost risk %  
+ Schedule risk factor x Schedule risk %**

- Risk Factors - from 1 to 15
- Risk Percentages - 1% to 4%
- Range of working allowance generated falls between 5% and 98%
- Best technical judgment used to override this specific graded approach to risk analysis



# Cost Estimate – Risk Factors

Risk Factor	Technical	Cost	Schedule
1	Existing design and off-the-shelf hardware	Off the shelf or catalog item	not used
2	Minor modifications to an existing design	Vendor quote from established drawings	No schedule impact on any other item
3	Extensive modifications to an existing design	Vendor quote with some design sketches	not used
4	New design within established product line	In-house estimate for item within current production line	Delays completion of non-critical path subsystem item
6	New design different from established product line. Existing technology	In-house estimate for item with minimal company experience but related to existing capabilities	not used
8	New design. Requires some R&D development but does not advance the state-of-the-art	In-house estimate for item with minimal company experience and minimal in-house capability	Delays completion of critical path subsystem item
10	New design. Development of new technology which advances the state-of-the-art	Top down estimate from analogous programs	not used
15	New design way beyond the current state-of-the-art	Engineering judgment	not used



# Cost Estimate – Risk Percentages

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	Condition	Risk Percentage
<b>Technical</b>	Design <u>or</u> manufacturing concerns	2%
	Design <u>and</u> manufacturing concerns	4%
<b>Cost</b>	Material cost or labor rate concern	1%
	Material cost or labor rate concern	2%
<b>Schedule</b>		1%





# Cost Estimate – Working Allowance

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- **This formulaic approach may seem mindless, however -**
- **It makes your estimators look carefully at each and every item at the lowest level**
  - » **Very valuable**
- **It provides a common point of departure for every estimator**
- **It helps in auditing each estimator and comparing with the practices of other estimators**
- **It has been applied successfully, and extended, by numerous projects:**
  - » **methodology thought to be started at TRW**
  - » **was adopted by magnetic fusion projects at Lawrence Livermore Labs**
  - » **then (about 12 yrs ago) was picked up by the GEM Detector effort (part of the US supercollider program)**
  - » **Currently in use by parts of the U.S. Large Hadron Collider (LHC) experiment funded by the US DOE**
  - » **Used by the STAR detector at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Labs**
  - » **Used by French CNRS and Atomic Energy Agency in their training**



# Cost Estimate – Working Allowance

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- **Estimate of working allowance made for each item at lowest practical level**
- **Percentage is converted to currency**
- **Working Allowance funds are held by the Project Manager and they lose their identification with each item!**
- **Each Task Leader controls the budget for a subsystem without the working allowance funds**
- **Remember that the working allowance pool is not designed to cover every possible risk that could occur during the Project**



# Request for Working Allowance Funds

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- **As the Project progresses, working allowance funds can be requested by written application to the Project Manager**
- **Requests are reviewed by Technical Board/Change Control Board consisting of all other system leaders**
- **Project Manager grants requested funds, or rejects request, or requests change in schedule, technical scope or requests other corrective action**
  - » **Scope allowance - require subsystem leaders to identify 10% reductions in subsystem scope**
- **Funds can be returned to the working allowance pool**



# Actual Costs and Estimate to Complete

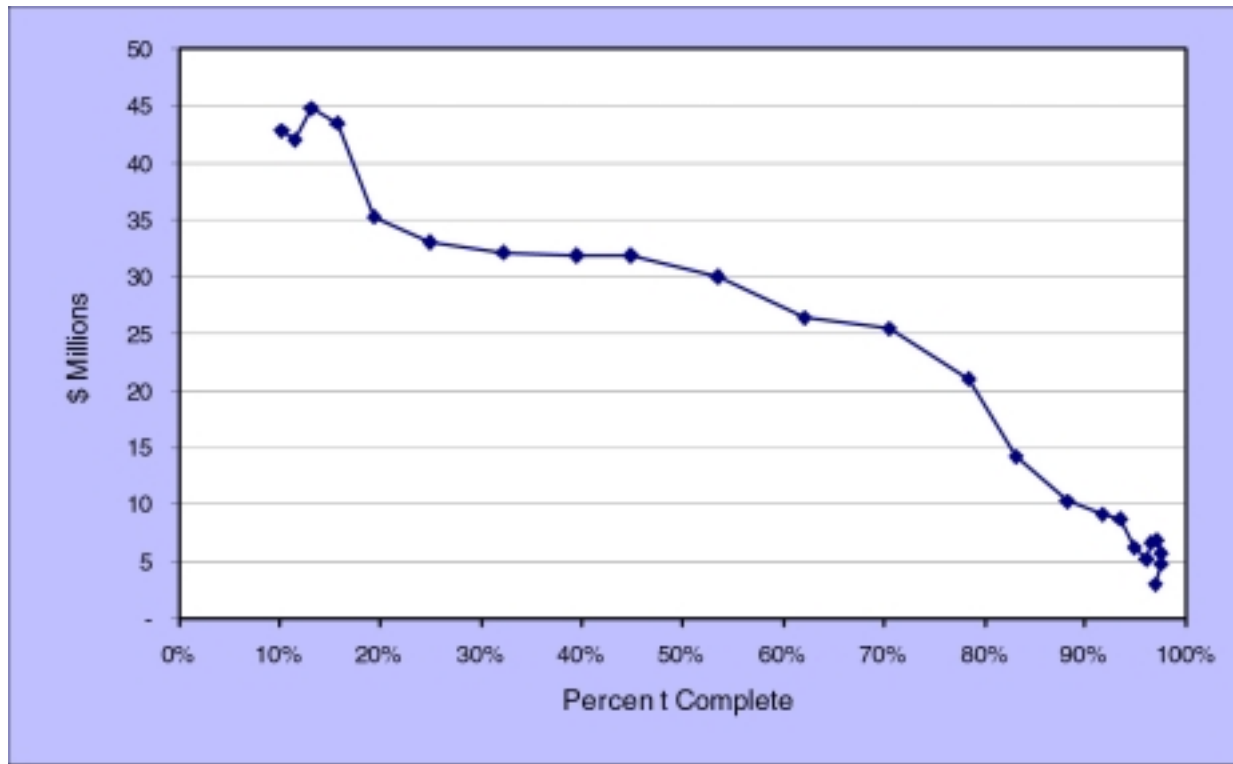
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- **If Project is estimated properly, 100% completion of Project will use 100% of direct estimate + working allowance**
  - » **Working Allowance is not to be hoarded till after project completion**
- **As Project progresses, direct cost estimate is exceeded and working allowance funds are used**
- **Periodically (annually?) cost estimate is revised to reflect all new information including actual costs and use of Working allowance funds. New estimate is called Estimate To Complete**
- **Track (%working allowance used)/(% Project complete)**



(% Working Allowance used)/(% Project complete)

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# Working Allowance in an International Collaboration

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- The NSF provides the working allowance to the LIGO project manager
  - » Gives the project manager the responsibility and the agility to respond to problems and changes quickly
- In an international collaboration it seems best that each partner maintains their own working allowance
  - » Each aware of the other's working allowance
  - » Partners consider pooling their working allowance resources iff a major perturbation occurs



# Spares Philosophy

- In-process Spares

- » Account for production yield on parts and assemblies, e.g

- Sensor/Actuator Assembly (alias OSEM) is spared at 50%, based on historical data on initial LIGO units which are used as the basis for the cost estimate:

- ~10% - magnet wire that shorts from the time that they are wound to the time that they are through unit test.
- ~5% - component failure after soldering and vacuum baking
- ~15% - non-uniform coating or poor adhesion which compromises electrostatic discharge capability (loose entire coating run)
- ~5% - PD/LED angular alignment is out of specification
- ~2% - fails RGA due to contamination
- ~5% - coil form rejected due to high surface roughness
- ~2% - ceramic circuit board failures in rework of cerama-bonds
- ~2% - broken or compromised during installation

- All of the above yield problems have potential solutions, some (not all) will add cost, above the current estimate

- We think that as the quality & yield improves, the total cost will remain about the same



# Spares Philosophy

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- In-process Spares (continued)
  - » Allowance for infant mortality or mishaps with critical parts to ensure maintaining installation/test schedule on critical path, e.g.
    - Electronics spared at level to support initial debug and commissioning (see below) at the system level
    - Historical data in initial LIGO suggests ~15% spares needed
    - Spares estimated at WBS lowest levels; quantization/site & engineering judgment cause the spares to range from 11% to 20%
  - » Engineering judgment and experience (if applicable)





# Spares Philosophy

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- **Delivered spares**

- » Spares explicitly itemized for delivery to enable an operational paradigm, e.g.
  - Spare suspension frames enable pre-assembly of a suspension, including integration of a spare optic, without bringing the interferometer out of operation and exposed to atmosphere for an extended period of time.
  - A number of occasions in LIGO when the capability to pre-assemble a suspension has helped to reduce the overall interferometer down time (failed fiber due to earthquake, mirror contamination, ...).
  - With an enormous observatory staff and commissioning team, the savings on the system level is well worth the investment.
  - Qty chosen by engineering judgment to be either 1 suspension type per observatory or per interferometer
- » Spares needed to support the commissioning period (see above)

- **Operational Spares**

- » Stocking and replacements for parts & assemblies
- » Not allowed as part of the construction effort; this is an operational expense