The Beauty of Hindsight: Advanced LIGO

24 May 2019

David Shoemaker
MIT
A Short History of aLIGO

- 1990’s: Many table-top and small-scale experiments in
  - Laser systems
  - Interferometer topologies
  - Mirror coating materials science
  - Extremely low-loss mechanical systems
  - Many degree-of-freedom servo control systems
- 1999: White paper, based on these ‘small science’ successes
- Early 2000s: LIGO Scientific Collaboration is born, refines design, shows strong scientific consensus and unity on the path forward
- 2003: Proposal to the NSF from the LIGO Laboratory
- Mid-2000’s: Advanced LIGO design refinement, hard choices, ‘Projectification’
The Project

● **2008: Project Start**
  ● $205M from the NSF, complemented by $15M UK, $15M Germany, $5M Australia (or so)
  ● **Scope:**
    » (design was separate from the Project, and done before/in parallel)
    » Remove and dispose of three old interferometers
    » Build three new interferometers
    » Install three interferometers
      ‒ Turned into install two, store one
    » Pay all staff time
    » Keep to schedule, and don’t ask for more money

● **2015: Project End**

● What could possibly go wrong?
Bad idea: try to do design on some subsystems while others are cutting metal

Led to rework, subsystems waiting for parts, thrash to keep ‘new, better ideas’ from being introduced

Not too much stuff thrown away

Auxiliary optics is the poster child here
Lumped together a bunch of stuff as we had in initial LIGO

» 1 transport of interferometer output beams,
» 2 stray light control,
» 3 thermal compensation (including diagnostic wave front sensing),
» 4 optical levers for alignment reference,
» 5 initial alignment procedure and equipment, and
» 6 the photon calibration/excitation system.

Underscoped cost and labor by about a factor of 6

Moral: make it 3-4 subsystems

Starved of early design and planning

Still working on stray light control today
Still learning how critical cleanliness is
  » ...point absorbers...
Knew we needed to scrub the interior of all the chambers
Did not know how much dirt we dragged in as humans
Tiger Team (Thanks Calum) attacked this problem
Changed garb requirements, glove manufacturers, etc.
Much *much* better now
...still not good enough.
RF Electronics

- Many radio-frequency oscillators
- Some of them slewing to track interferometer lengths
- Too much RF radiated and carried in grounds
- Enough nonlinearities to mix everything in sight
Subcontractor monitoring

- QA/QC was invented and executed in house, with a light touch
- Production in the Lab worked out ok
- Had some dramatic problems with subcontractors
  - Holes drilled in wrong places, filled with plugs, and *intentionally* hidden
    - …found after assembly of seismic isolation systems
    - Disassembly, new fab, clean, reassemble
    - Time = money; this cost time AND money
- Next time: heavier touch on QA/QC
Labor estimates

-Asked subsystem leaders with experience in initial LIGO to estimate labor and its uncertainty
-Followed with lead system engineers, in general increasing estimates and uncertainty
-Followed with a MonteCarlo study (Thanks, Carol) to estimate a roll-up of costs covering a range of uncertainties
-And...
-Underestimated Labor by something like a factor of 2 – a huge cost for aLIGO (all labor was paid by the Project).
-How did we survive?
  » Estimates from fab houses collected in dot.com years – all high
  » aLIGO contracts let after dot.com bubble burst – fab costs were lower than expected.
  » We got lucky – fab money could pay for people
Project Management

- Project management infrastructure and software
  - Required by the NSF to do ‘earned value tracking’ and to report voluminously on spending
  - Also needed to be agile for changes – late mirror coatings, LIGO-India shift, etc.
  - Basic incompatibility for the tools we used (Primavera, Prism)
  - Also: software needed experts for input, and to interpret output
    - Many project controls people required ($$$)
    - Technical leaders felt disconnected from process

- Project management communication
  - Because it felt imposed, and project controls people were not savvy on our technology, little buy-in from tech staff
  - Subsystem leaders did not want to spend time on it and in fact did not have the time – ‘Do you want the paperwork or the subsystem?’

- Project management did not feel like a tool to the team but instead like a burden
  - (but absolutely necessary)
Geographically dispersed subsystem teams

- Initial LIGO had suffered from having people in a given team at the 4 Lab sites (Caltech, MIT, LLO, LHO)
  - Disconnects, miscommunication, duplicated effort, travel costs...
- We swore never to do it again...
- ...we did it again.
- No choice: the experts were spread around.
- aLIGO could profit from iLIGO – people either had already worked distributed, or had been at e.g., MIT then moved so already ‘a team’
- (there are also advantages – cross-checking, more breadth in background, teams at observatories had ownership and were not shipped black boxes)
Much much better than in iLIGO
But still too little too late
Spent the last 6 months scrambling to get basic documentation in place
But lacking a critical scope: running and debugging
Also need to maintain and refine documentation during running
  » Extra site burden – needs documentation staff to shadow commissioners
  » Very, very hard to do real detailed detector characterization if not at a site, limiting severely the number of people who can help
aLOG is very useful, but could consider a system which also builds and corrects documentation as aLOGs are made using a collection of keywords
Delaying decisions

- aLIGO had very valuable external committees
  - LIGO PAC
  - aLIGO PAP

- They told us again and again:
  - Make decisions early on imperfect knowledge – take risk
  - Spend money early to save time (and thus money) later

- We did a little of it but not anywhere near as much as we should have

- Would have had the resources to fix most of the persistent problems if we had.

- But despite all that…
Happy Ending

- Completed
  - within budget
  - on schedule
- Detections were made
- We are eager to do it again
  - …and make new mistakes