LIGO

Aspects of Operations & Maintenance at GW Observatories

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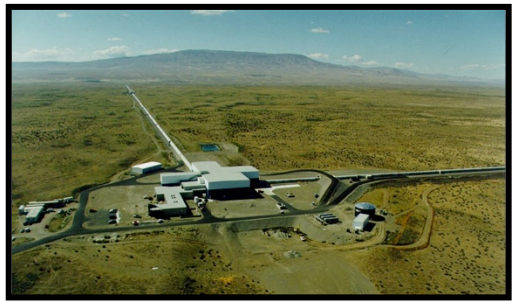
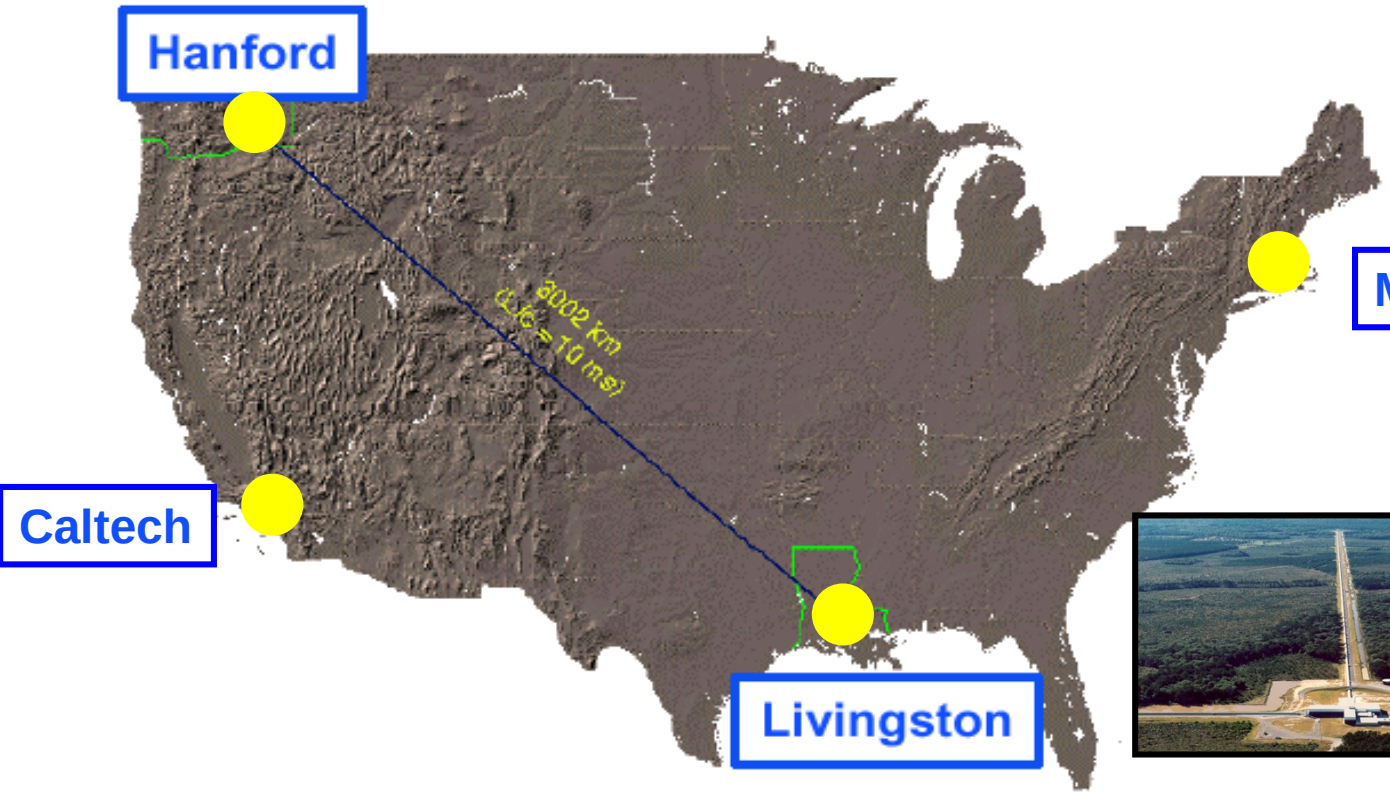
NSF Large Facilities Workshop, May 2017

LIGO Laboratory: two observatories, Caltech and MIT campuses



- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



LIGO Laboratory's Overall Mission

- **Advanced LIGO Detectors – commission the newly constructed Advanced LIGO to design sensitivity**
- **Physics/Astrophysics Research - direct detection of gravitational waves and development and exploitation of gravitational-wave astronomy**
- **Precision Interferometry Research – research and development to upgrade and improve Advanced LIGO detectors**
- **Facilities - operate and maintain the LIGO Observatories and campus facilities**
- **Education and Public Outreach – develop scientific education and public outreach related to gravitational wave astronomy**
- **Develop the Global network – develop the international gravitational wave community to coordinate gravitational wave observations; support the construction of LIGO-India**

(Condensed from the LIGO Lab Charter)

Operation and Maintenance

The LIGO detector must run 7x24 during runs (since Nature can send events at any time

- **O&M** of Advanced LIGO detector, incremental sensitivity and robustness improvements.
- **O&M** Site and Facility and Vacuum equipment maintenance (now 20+ yrs. old)

Some Major Facility Lifecycle Renewals completed ahead of O1.

- **Re-roofing of Twelve original roofs & reinstall lightning protection- Completed Feb 2014 as specified with a 20 year warranty**
- **Renew original Main and End station chillers: 6 new & 1 refurbished- Completed Feb 2014**

LIGO

Observatory Sites overview

- Sites:
  - LHO:1500 acres, LLO:180 acres.
  - Erosion control, flood control, grass, tumbleweed mowing/abatement.
  - Access control/ security.(LLO ~ 16km of border with forestry & hunters)
  - 13+ miles of paved access roads.
- Facility:
  - Potable water supplies and sewerage; treatment, testing and permitting.
  - Fire water storage, distribution, pumps, hydrants, sprinklers maintained to code. Fire control systems within buildings, including clean agent systems for critical electronics and computers.
  - 13.6 kV 3-phase power distribution to 480 V 3-phase panels, special balanced 117 V technical power for detector electronics.
  - Clean room lab areas, with HEPA-filtered air and contamination control protocols, precise temperature and humidity control, special low-vibration HVAC fans, remote chillers and plenum space to reduce temperature gradients, overhead cranes, fork lift trucks, aerial lifts, etc.
  - Office space, auditorium for collaboration and outreach meetings.
- Need to maintain facilities anticipating 20+ more years of operation.

Threat/ Disaster Management

Environmental Threats that affect sites and staff:

- **LIGO Livingston:** Hurricanes, tornadoes, heavy rain, flooding, lightning, high humidity, heat stress management, critters….
- **LIGO Hanford:** Snow, icy roads, extreme cold, extreme heat, scrub fires, tumbleweeds, critters…
- **Lesson learned:** Have a plan and fit in with what the community does.
  - For example, when New Orleans is likely to evacuate, normal commerce and transportation is impossible in the Livingston area, so we close our gate valves and evacuate the site. This must be done days before a hurricane landfall.

Property Lifecycle Maintenance Plan: Asset Condition Report

- LIGO M&O Cooperative Support Agreement (CSA) for FY2014-FY2018
- "Subject to the availability of funding, the Awardee will provide by October 1, 2016 an Asset Condition Report evaluating the remaining life of civil infrastructure at the LHO and LLO sites, and estimating the cost of significant replacement or refurbishment to be scheduled during Oct 1, 2018 - Sept 30, 2023."

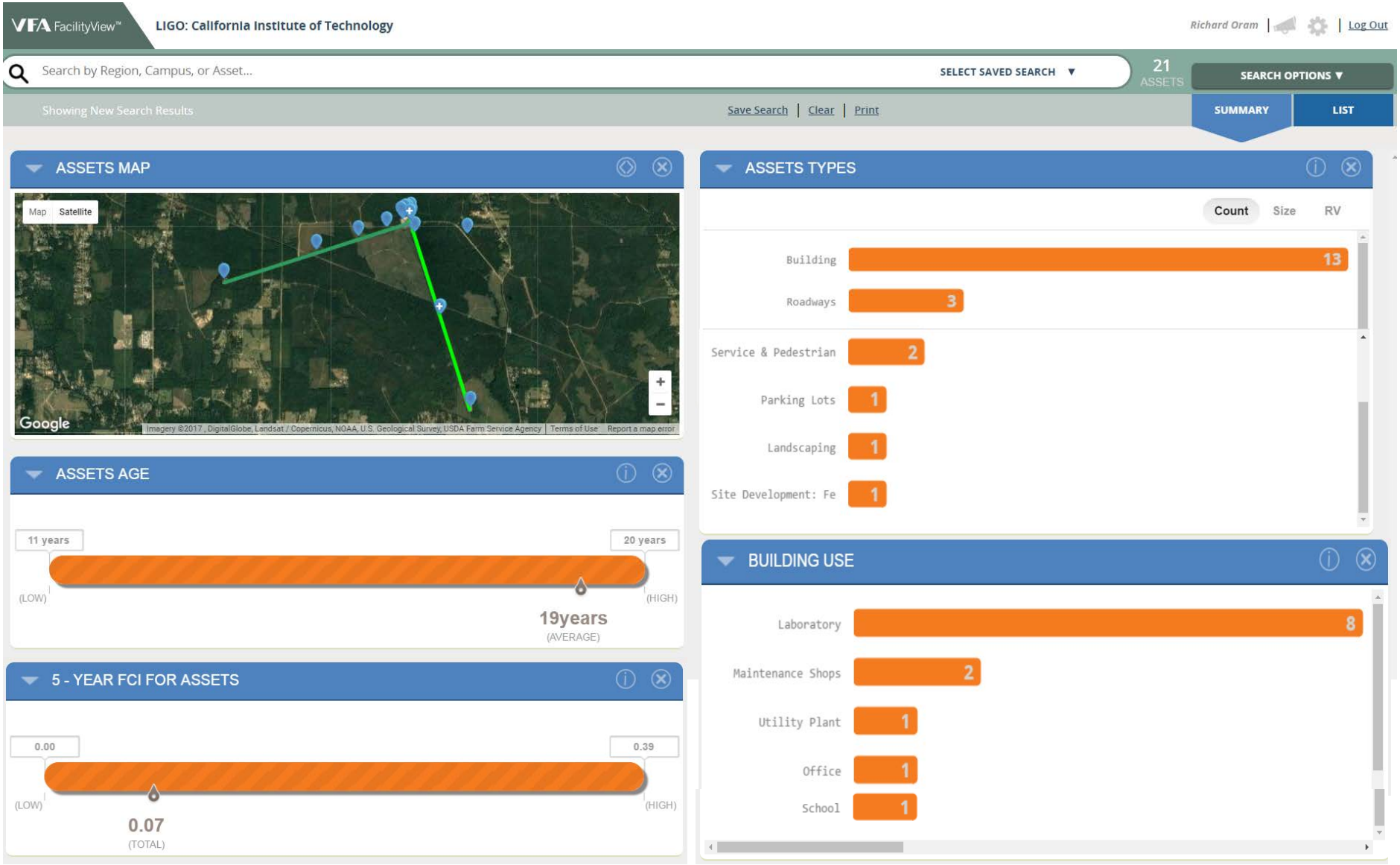
- In response LIGO selected a consulting civil engineering firm ([1]VFA inc., part of Accruent LLC.) and completed a condition assessment of the sites and provide staff training during July 2016.
- The data from this assessment are now entered into web based VFA.auditor and will be used for future maintenance management, capital planning & budgeting and report generation.

[1]VFA, Inc (an accruent company)- http://www.vfa.com/

Property Lifecycle Maintenance Plan Plan Development

- The VFA assessment team consisting of an architectural, mechanical, and an electrical consultant performed assessment inspections of 26 buildings and associated assets (13 buildings each at LLO and LHO).
- The VFA assessment team used the **ASTM standard (E1557-09 (2015)) Uniformat II Classification for Building Elements-** classifying building specifications, cost estimating, and cost analysis. The elements are major components common to most buildings.
- **Uniformat** estimating applies unit-cost data to building-system and component site elements. This "systems" approach uses a hierarchical structure of cost elements, beginning at Level 1 with basic systems, such as Substructure, Exterior Enclosure, and Interior Construction, and proceeding to successively more detailed subdivisions of these systems at Levels 2-5. See GSA.gov.- Uniformat.
- Estimates for Systems and Requirement Actions were made using RSMeans tables for 2016. RSMeans supplies construction cost information for North America used to estimate the costs of construction and renovation projects. For more information on RSMeans, go to www.rsmeans.com.

Property Lifecycle Maintenance Plan
VFA Facility and FacilityView



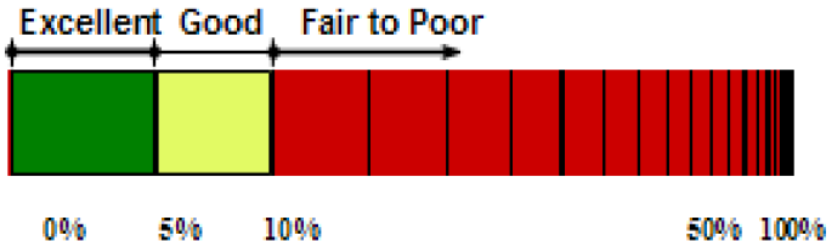
The Facility Condition Index (FCI)

- **The Facility Condition Index (FCI), a standard used to indicate the condition of an asset or assets, is the ratio of the cost of requirements divided by the current replacement value (CRV) of the asset. The CRV is the total value of all systems that make up a particular asset. The lower the FCI value the better the condition of the building or asset.**
- **The FCI is calculated as:**

$$\text{FCI} = \frac{\text{Total FCI Requirements}}{\text{Current Replacement Value}}$$

- **FCI calculations result in the determination that each asset or assets fall into the qualitative description of excellent, good, fair or poor. The lower the FCI value the better the condition of the building.**

FCI	
Excellent	0.00 to 0.05
Good	0.05 to 0.10
Fair	0.10 to 0.15
Poor	Greater than 0.15



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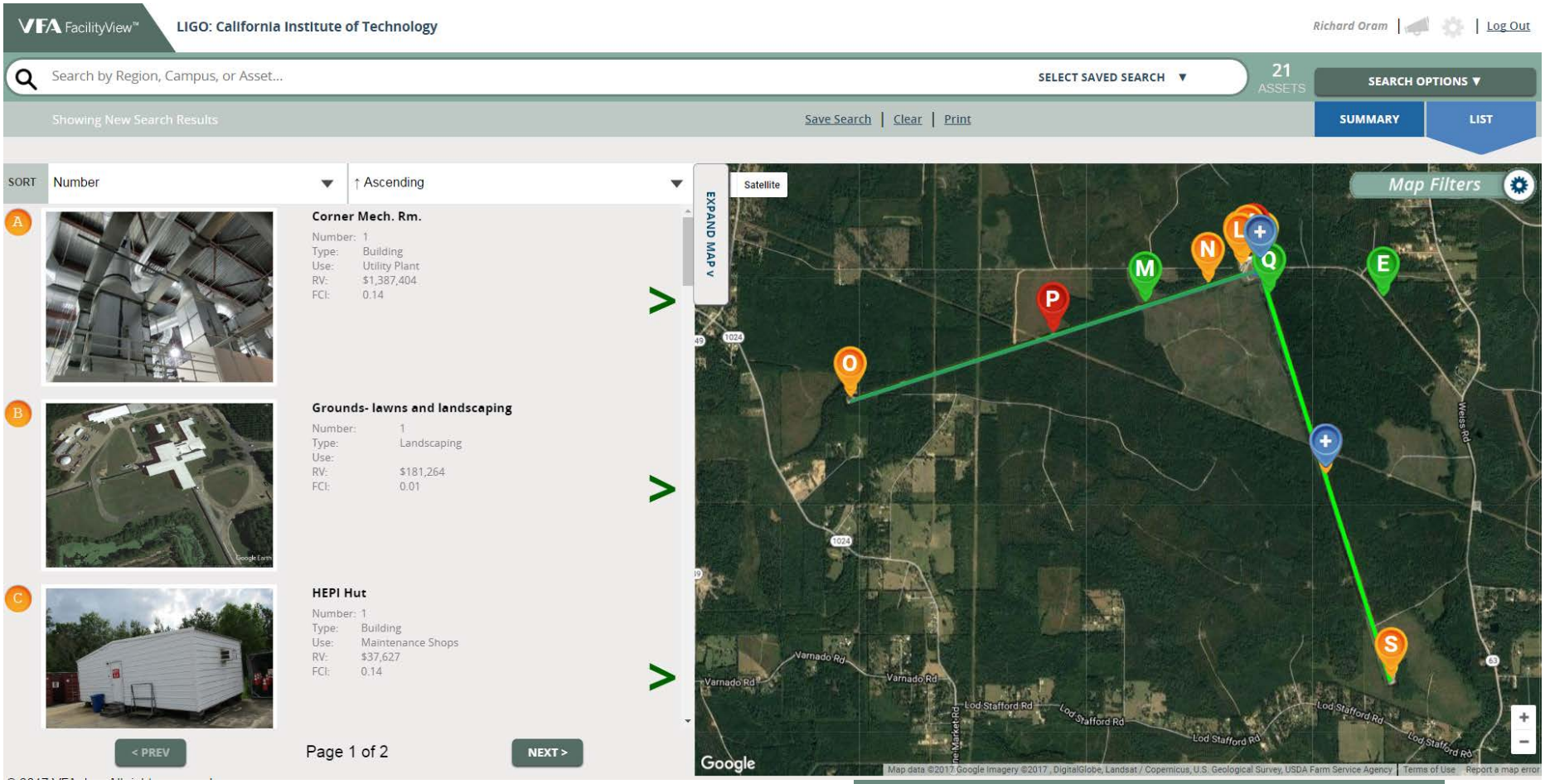
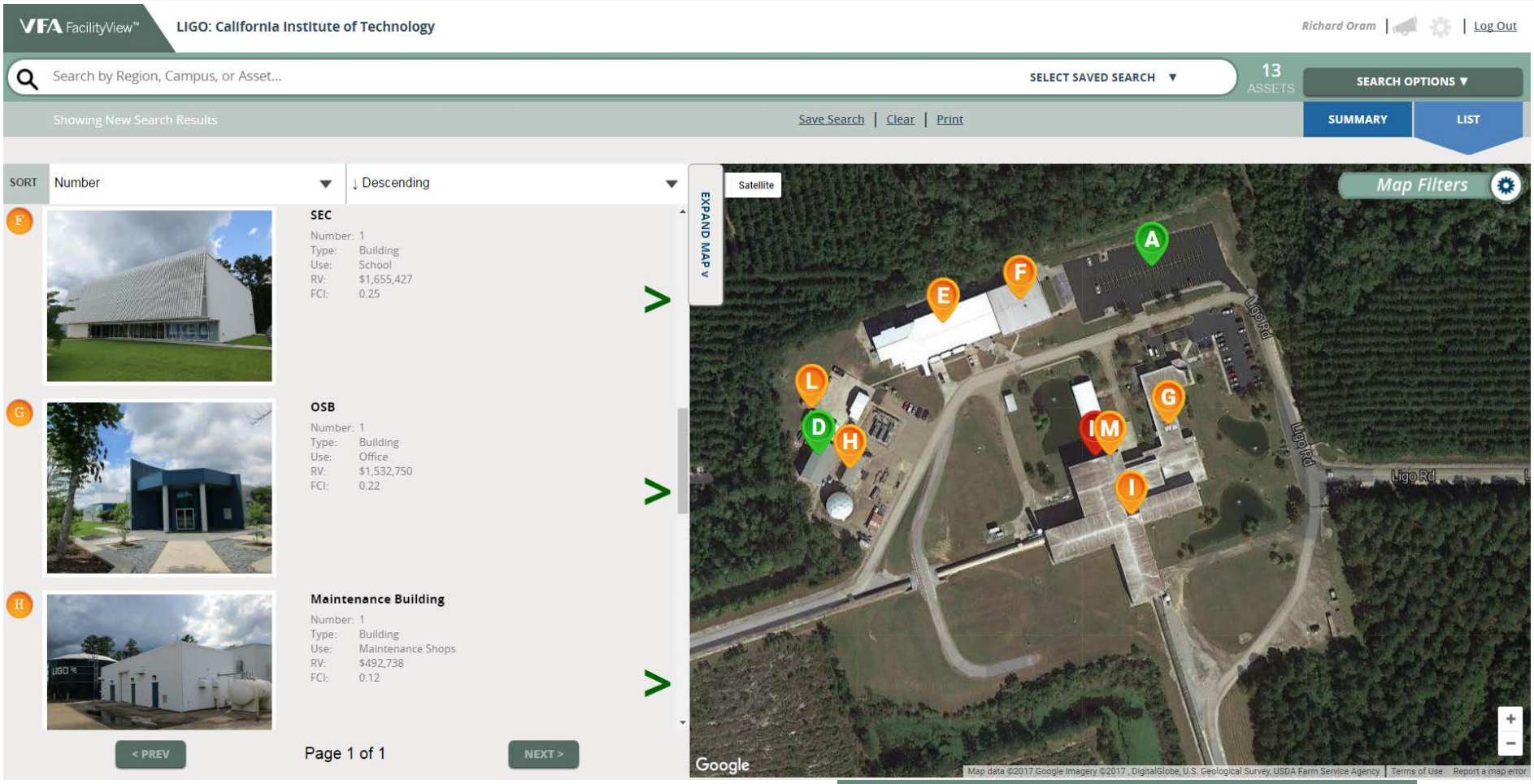


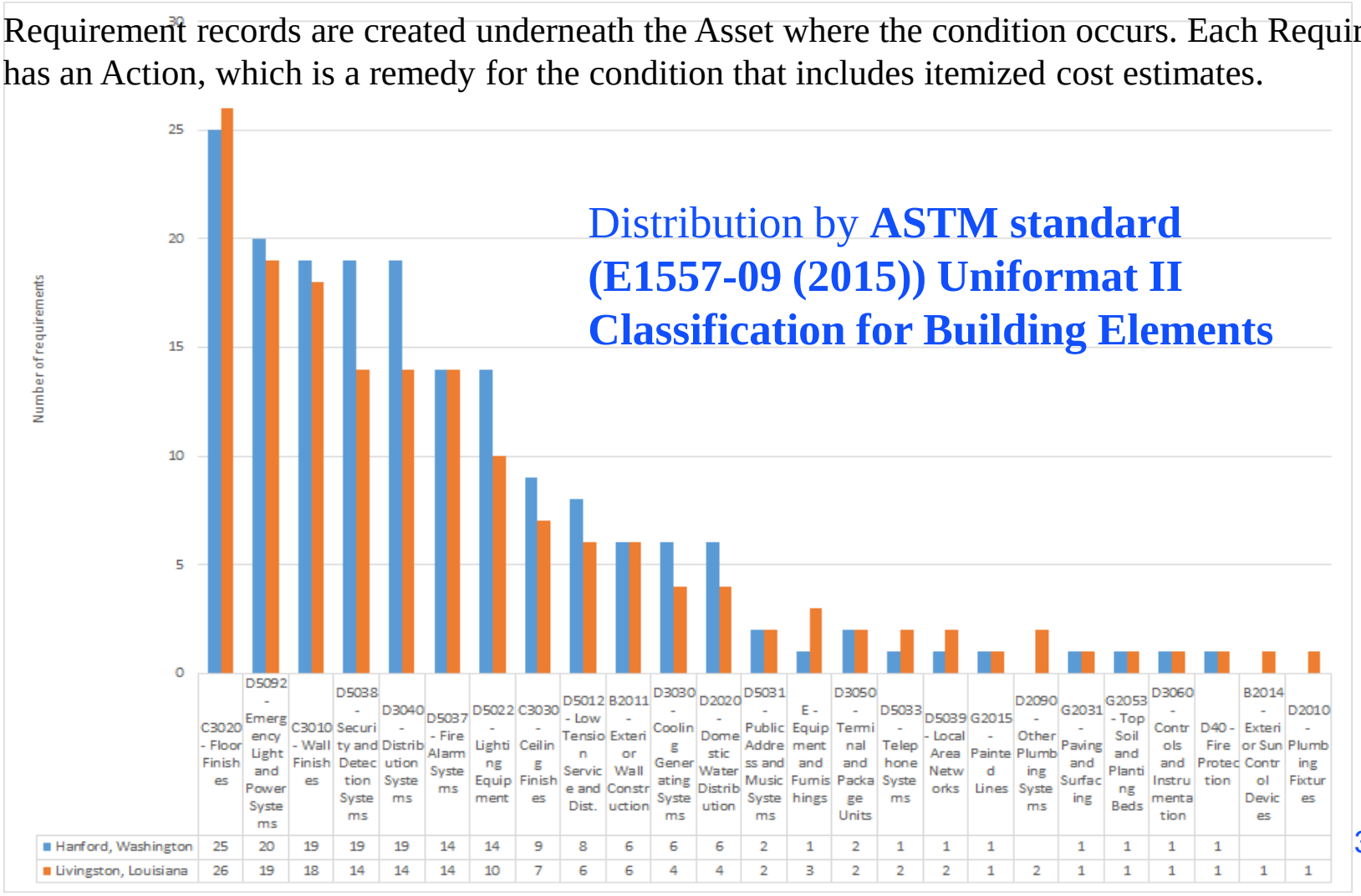
Property Lifecycle Maintenance Plan
VFA Facility and FacilityView



Property Lifecycle Maintenance Plan FY2019 – 2023

Total of 339 Requirements/Renewals over Five years.

- A Requirement is a facility need or a deficient condition that should be addressed, including deferred maintenance, code issues, functional requirements, and capital improvements.
- Requirement records are created underneath the Asset where the condition occurs. Each Requirement has an Action, which is a remedy for the condition that includes itemized cost estimates.



	C3020 - Floor Finishes	D5092 - Emergency Light and Power Systems	C3010 - Wall Finishes	D5038 - Security and Detection Systems	D3040 - Distribution Systems	D5037 - Fire Alarm Systems	D5022 - Lighting Equipment	C3030 - Ceiling Finishes	D5012 - Low Tension Service and Dist.	B2011 - Exterior Wall Construction	D3030 - Cooling Generating Systems	D2020 - Domestic Water Distribution	D5031 - Public Address and Music Systems	E - Equipment and Furnishings	D3050 - Terminal and Package Units	D5033 - Telephone Systems	D5039 - Local Area Networks	G2015 - Painted Lines	D2090 - Other Plumbing Systems	G2031 - Paving and Surfacing	G2053 - Top Soil and Planting Beds	D3060 - Controls and Instrumentation	D40 - Fire Protection	B2014 - Exterior Sun Control Devices	D2010 - Plumbing Fixtures
Hanford, Washington	25	20	19	19	19	14	14	9	8	6	6	6	2	1	2	1	1	1		1	1	1	1		
Livingston, Louisiana	26	19	18	14	14	14	10	7	6	6	4	4	2	3	2	2	2	1	2	1	1	1	1	1	1

Property Lifecycle Maintenance Plan: Peer Review

- **NSF review recommendation:**
  - "Have the Property Life Cycle Maintenance Plan peer reviewed and vetted by maintenance professionals from a similar large science facility (e.g. JPL, Fermilab, etc.) annually."

- **We now include Lifecycle maint. section in LIGO's Annual Work Plan:**
  - The property lifecycle plan is a list of planned activities and budgetary estimates for accomplishing maintenance activities.
  - LIGO is now conducting this peer review activity with appropriate external reviewers from ESO, Fermilab and Smithsonian facilities.

Some unique aspects of maintenance @ GW Observatories

Always being conscious of need to be quiet in the work that we do.

- Site maintenance activities and equipment adjusted for minimum disturbance (vibration and E/M interference).

Weekly Preventive Maintenance squeezed into a Four hour period every Tuesday 9 am – 1 pm. (LLO and LHO nearly coincident)

- Use of CMMS (FAMIS) to organize and schedule Tuesday PMs
- Contractors provide service and regular maintenance during 4 hour/week period.
- Rigorous use of work permit process to communicate, approve and de-conflict non-routine work

LIGO-specific considerations:

- LIGO Lab members are part of the LIGO Scientific Collaboration, so we are part of our user community. Various LSC members contribute to O&M.
- GW science greatly rewards even small range improvements, so steady-state operation often includes incremental improvements.

Improved Operational Processes:
Computerized Maintenance Management System (CMMS)

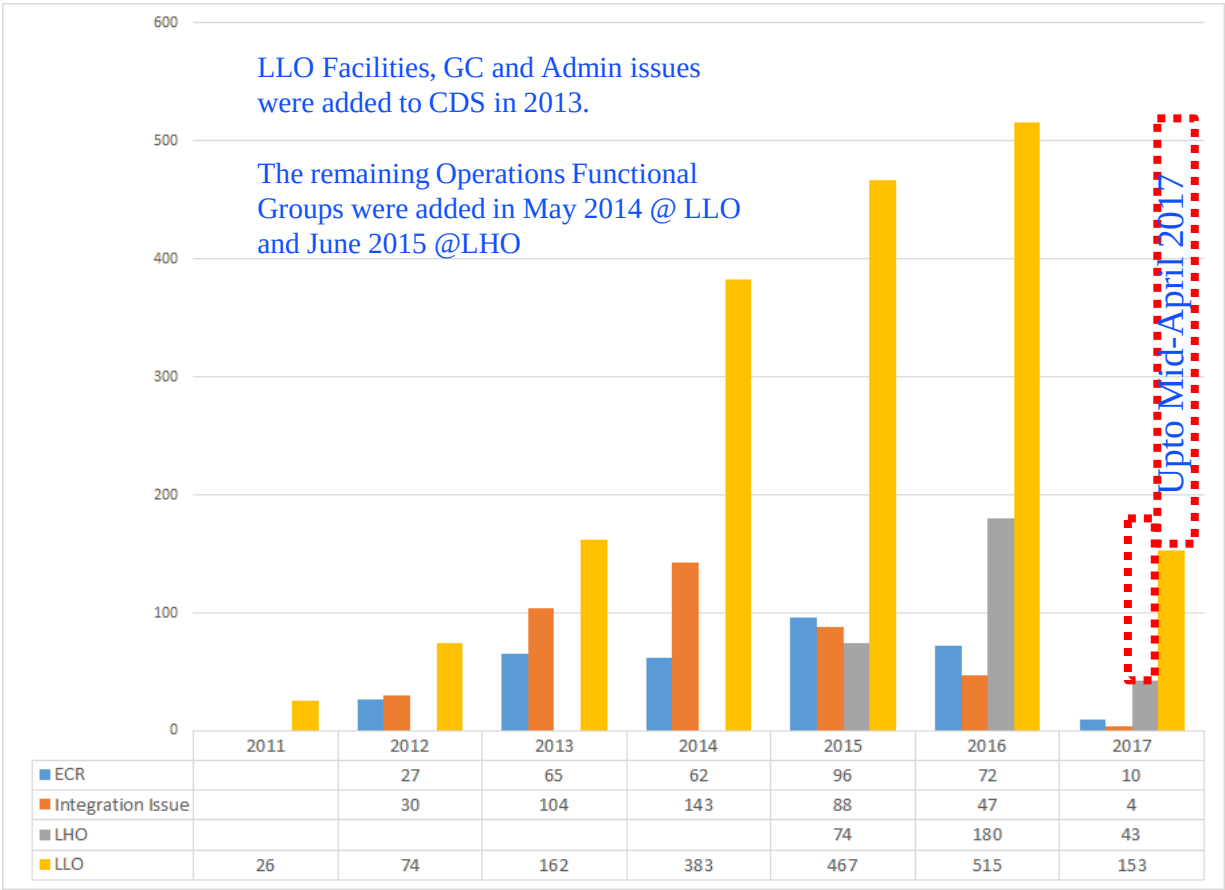
- **Computerized Maintenance Management:**
  - ***Preventative Maintenance*:** planned and organized using FAMIS cloud based CMMS
  - ***Corrective Maintenance, Integration issues*:** reported and tracked using customized bugzilla software, locally called FRS (Fault Reporting System). Software bugs/features tracked with bugzilla instances.
  - "Process Flow for Engineering Operations of the LIGO Detector Systems".
    - Rigorous use of work permit process to communicate, approve and de-conflict non-routine work
  - Spares procurement and planning.
    - Non-detector (infrastructure) spares to be tracked in FAMIS.
    - Detector spares tracked using aLIGO-developed Inventory Control System ICS.
- Performance monitoring and reaction:
  - Key performance indicator "dashboard."
  - In weekly reviews, recurring faults are noted and receive additional analysis, as are faults that cause significant downtime.
- Facility Asset Condition Report completed.
- Property life-cycle maintenance plan, budgets and tasks for maintenance, now formally part of annual work plan:

Computerized Maintenance Management System

Operations Management Team: Bug 33 - OMT charge to implement maintenance database services for both Observatories

- **Corrective Maintenance (FRS): In progress:** Daily use of the Fault Reporting System (FRS) to improve response time and quality of service provided to fault reports and service requests. Operations groups now daily use operational data (from aLOG, FRS, Work Permits) to prioritize and schedule daily/weekly work plans and drive decisions.

- **LHO/LLO** roll out of **FRS 2.0** combined FRS & Integration Issues & ECR Tracker : The CMMS team members along with LIGO Systems Engineering have defined requirements (FRS 2.0 user's manual: T1400332) for a unified implementation of the FRS (for both observatories) together with the functionality of the aLIGO integration issues tracker



	2011	2012	2013	2014	2015	2016	2017
ECR		27	65	62	96	72	10
Integration Issue		30	104	143	88	47	4
LHO					74	180	43
LLO	26	74	162	383	467	515	153

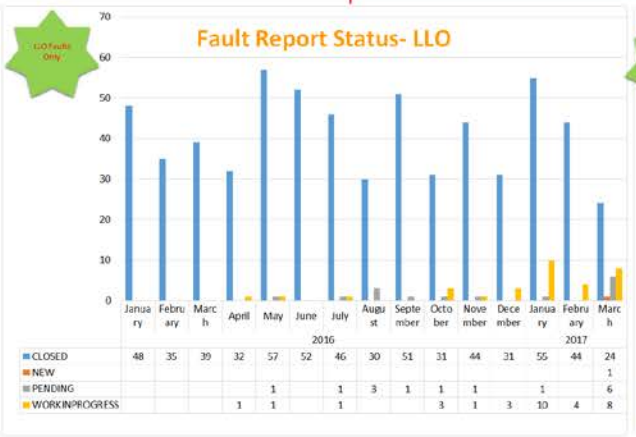
Activity: Operations use of FRS

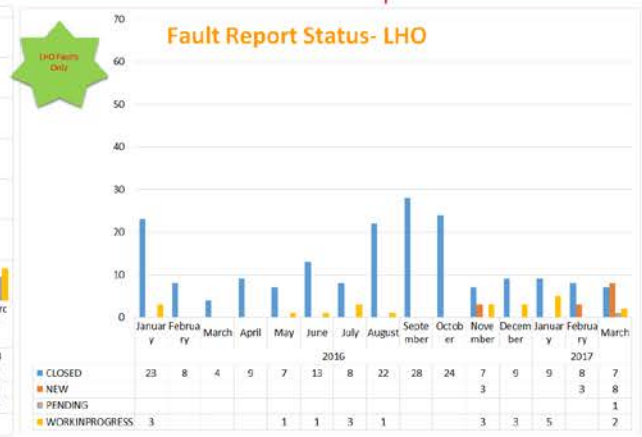
Key Performance Indicators

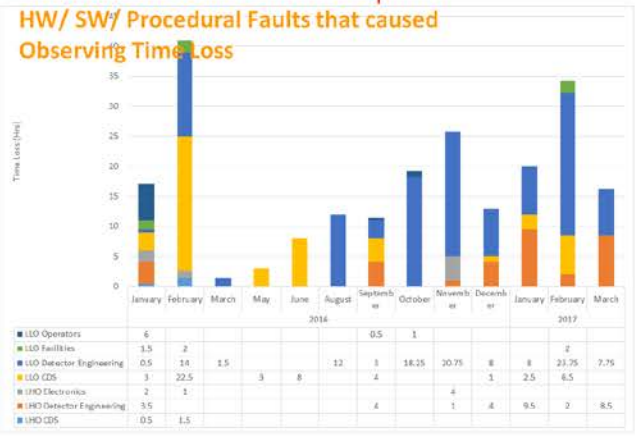
https://services.ligo-la.caltech.edu/FRS

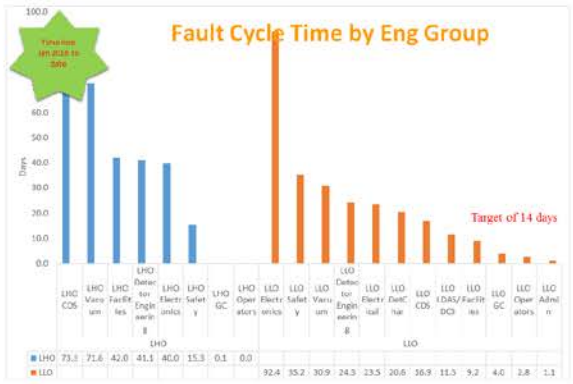
FRS Performance Metrics

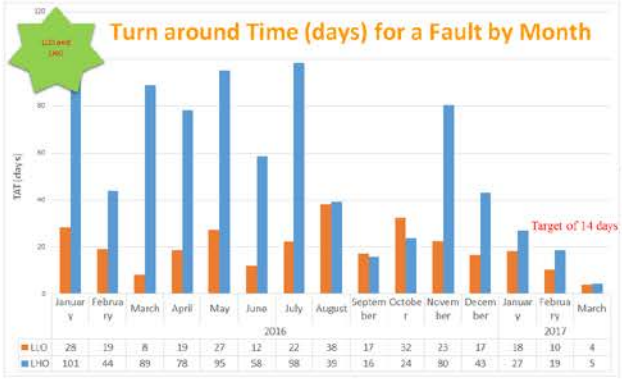
Key Performance Indicator Dashboard

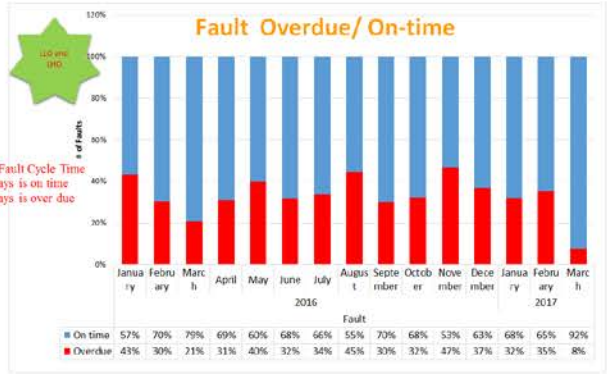












Link to Weekly Key Performance Indicator Dashboard is https://services.ligo-la.caltech.edu/KPI

Observatory Operations

Observing time scheduled into Observing blocks - O1, O2, O3 etc. punctuated by Commissioning periods, Planned Engineering and Engineering Runs (~month)

aLIGO Observing runs.

O1 ~ 4 months,
O2 ~ 6+ months
O3 ~ 12+ months

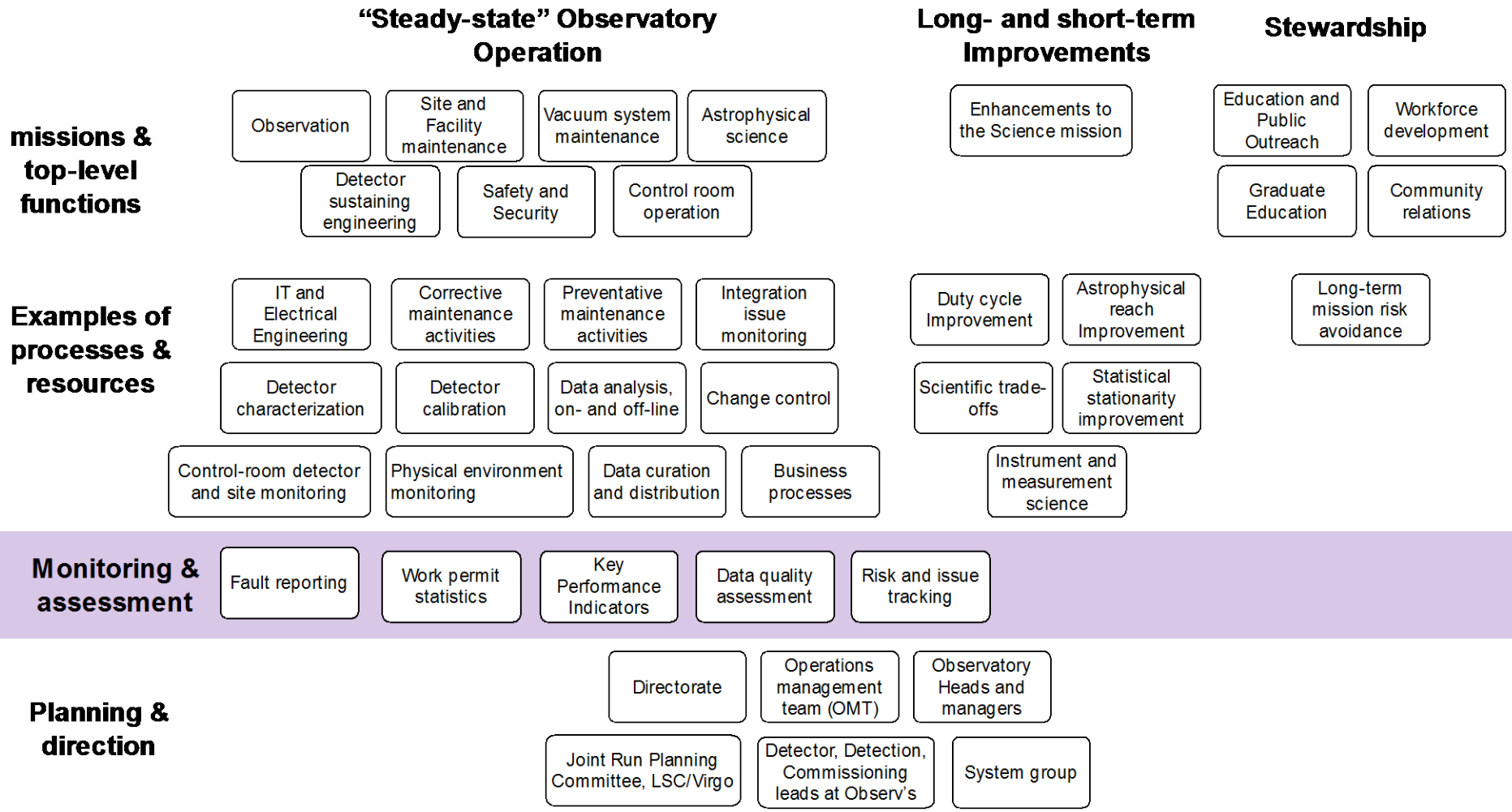
Control room is staffed 24/7 by "on-duty operator" during observing runs to monitor and operate detector, maximize uptime and provide safety.

Weekday support and then overnight and weekend "On-call" by team of Detector Engs, Scientists, SWE, EE, Facility and Vacuum Eng. and Managers.

Observatory operations hinge upon the goodwill and professionalism of the amazingly dedicated staff.

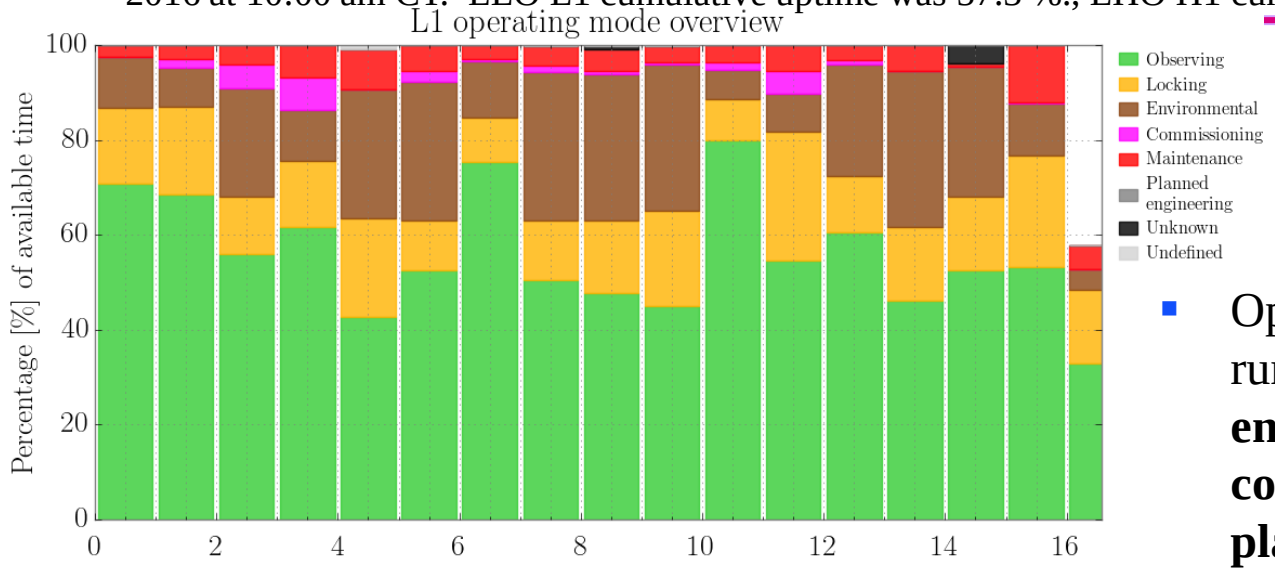
Staff assignments are adjusted, and family life altered to operate detector as reliably as possible.

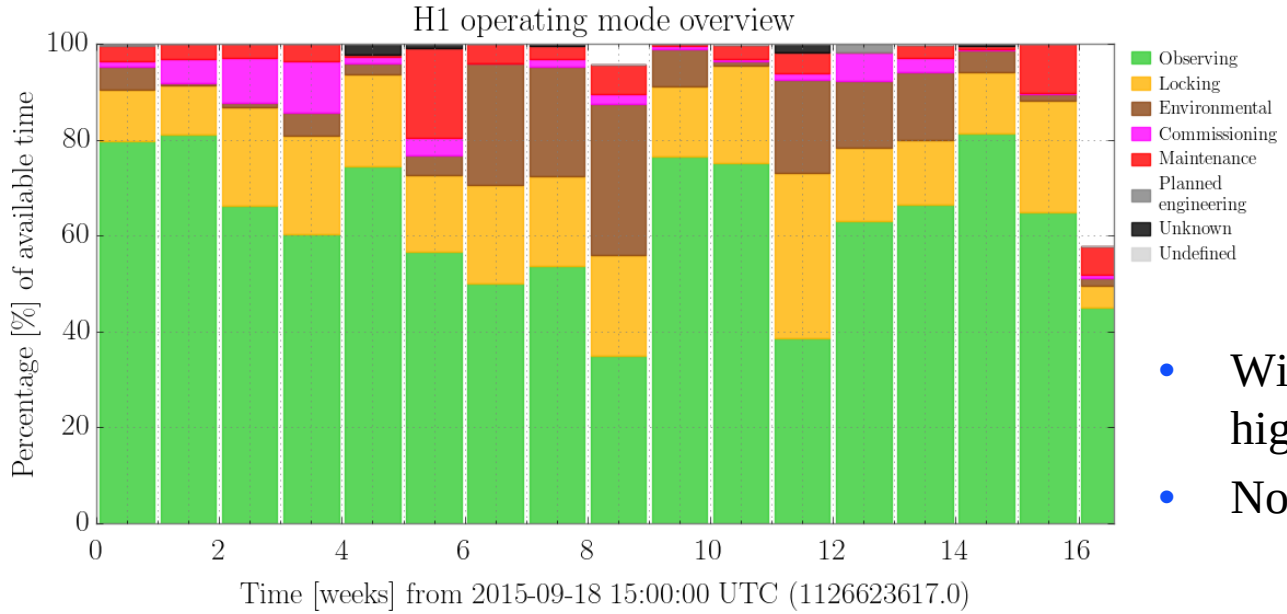
A large number of functions, resources and tools, organized by specialized teams



O1 Performance: Observing summary

O1, which began at 10:00 am CT on September 18th, 2015. O1 ran for 16 weeks and 4 days and ended January 12th 2016 at 10:00 am CT. LLO L1 cumulative uptime was 57.3 %., LHO H1 cumulative uptime was 64.6 %.,



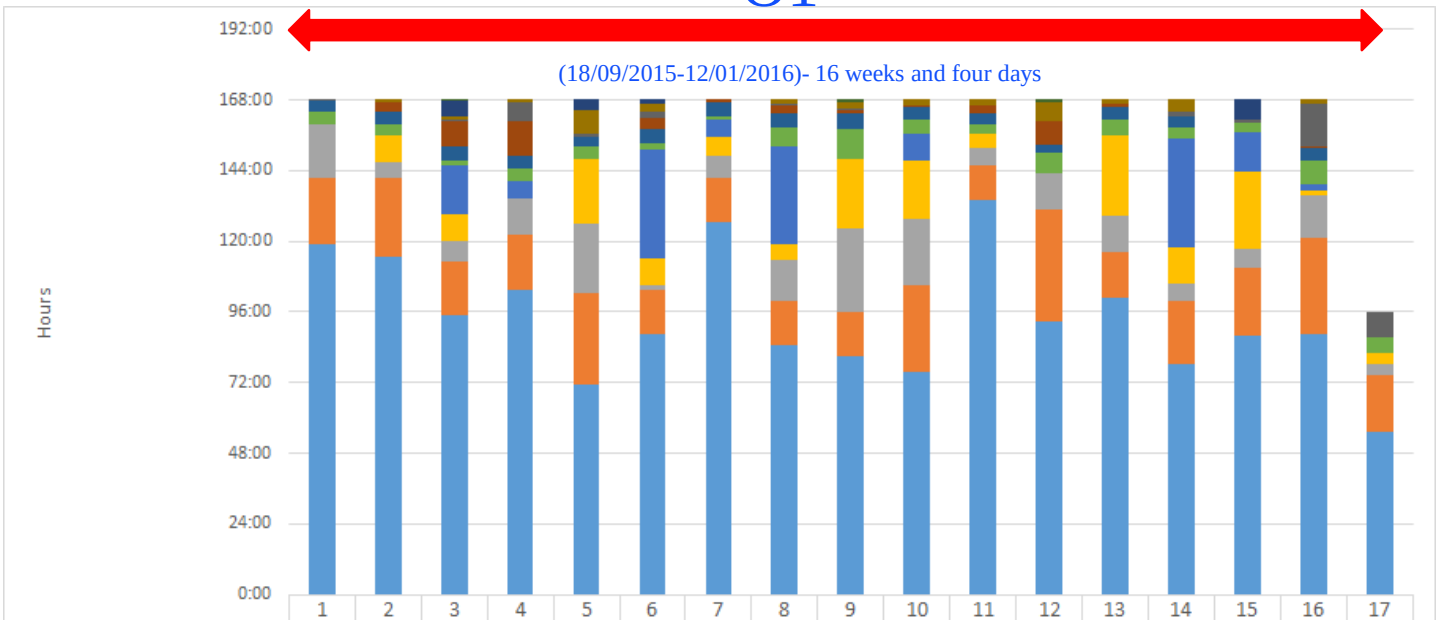


- Operators tracked status during run, **observing**, **locking**, **excess environmental noise**, **commissioning**, **maintenance**, **planned engineering**, etc.

- Winter run included expected high ground motion and storms
- No evident trends.

LLO O1 Performance: Observing summary

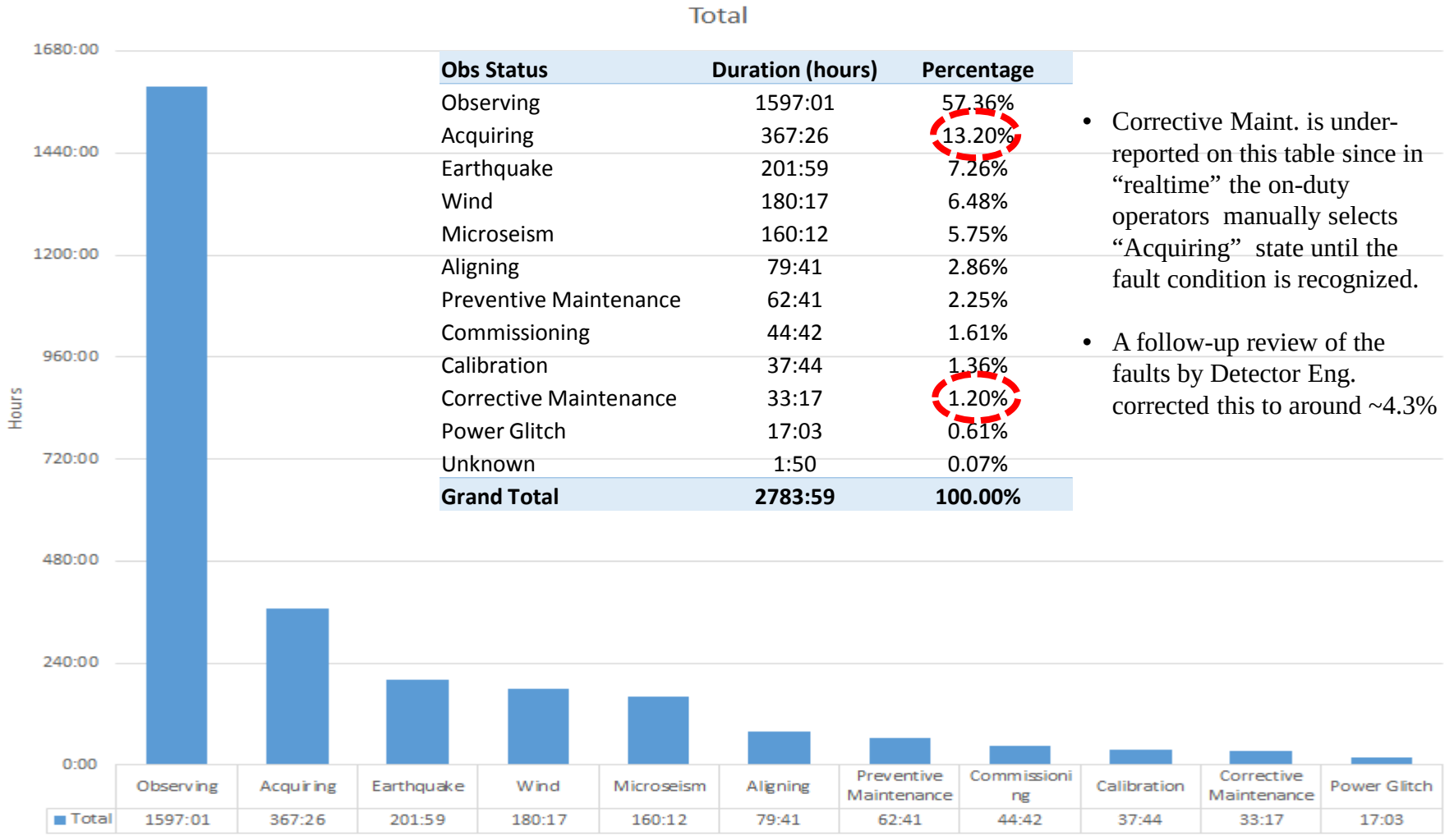
O1 L1 cumulative uptime was 57.3 %; Observing Time Loss due to HW/SW/Procedural faults was 120.8 hrs (~4.3 %)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Unknown			0:01						1:00			0:48					
Power Glitch			5:27		3:25	1:28									6:41		
Corrective Maintenance		0:48	1:05	1:04	8:12	2:40		1:09	1:48	1:48	1:59	6:18	1:05	3:55		1:21	
Calibration	0:29		0:48	6:25	0:44	2:04		0:48	0:51					1:31	0:52	14:39	8:28
Commissioning		3:12	8:29	11:37		3:44	0:35	2:33	1:05	0:49	2:41	8:01	1:32			0:20	
Preventive Maintenance	3:35	4:06	4:53	3:59	3:21	4:35	5:08	4:52	5:08	4:01	3:51	2:55	4:12	3:46		4:12	
Aligning	4:07	4:05	1:39	4:38	4:29	2:14	1:04	6:21	10:00	4:45	3:02	6:40	5:21	3:55	3:26	8:12	5:34
Microseism			16:28	5:53		36:46	6:02	33:10	0:04	9:14				37:11	13:07	2:10	
Wind		9:09	9:11		22:05	9:16	6:12	5:20	23:26	19:55	4:54		27:04	11:58	26:15	1:32	3:55
Earthquake	18:13	5:21	6:43	12:02	23:30	1:41	7:37	13:53	28:29	22:33	5:45	12:41	12:24	6:09	6:48	14:39	3:24
Acquiring	22:29	26:32	18:23	18:54	30:38	14:49	14:47	15:12	15:10	29:32	11:31	37:59	15:44	21:00	22:44	32:30	19:23
Observing	119:04	114:42	94:48	103:23	71:32	88:38	126:31	84:37	80:54	75:19	134:14	92:33	100:34	78:30	88:03	88:20	55:13

LLO O1 Performance: Observing summary

- O1, which began at 10:00 am CT on September 18th, 2015 ran for 16 weeks and 4 days (2784 hours) and ended January 12th 2016 at 10:00 am CT. The LLO L1 cumulative uptime was 57.36 %.



Obs Status	Duration (hours)	Percentage
Observing	1597:01	57.36%
Acquiring	367:26	13.20%
Earthquake	201:59	7.26%
Wind	180:17	6.48%
Microseism	160:12	5.75%
Aligning	79:41	2.86%
Preventive Maintenance	62:41	2.25%
Commissioning	44:42	1.61%
Calibration	37:44	1.36%
Corrective Maintenance	33:17	1.20%
Power Glitch	17:03	0.61%
Unknown	1:50	0.07%
Grand Total	**2783:59**	**100.00%**

- Corrective Maint. is under-reported on this table since in "realtime" the on-duty operators manually selects "Acquiring" state until the fault condition is recognized.
- A follow-up review of the faults by Detector Eng. corrected this to around ~4.3%

LIGO

O1 Performance:

Detector Engineering Operations & Maintenance: O1, which began at 10:00 am CT on September 18th, 2015. O1 ran for 16 weeks and 4 days and ended January 12th 2016 at 10:00 am CT.

The L1 and H1 detectors achieved an NS-NS inspiral range of ~60-80 Mpc during O1; No major Commissioning breaks or interventions were necessary.

LLO L1 cumulative uptime was 57.3 %., LHO H1 cumulative uptime was 64.6 %. Double Interferometer cumulative uptime was 42.8 %.

LLO:Observing Time Loss due to HW/SW/Procedural faults was 120.8 hrs (~4.3 %).

Opportunities for Improving Observing uptime > 60%: (Any low hanging fruit ?)

- Better strategies for maximizing coincident observing. (PMs, no risky WP)
- Streamlining “acquiring process” (>10%)
- Wind and microseism remediation (>12%) (somewhat seasonal, run planning?)
- Power glitches (~1%)

O1 & O2 Performance: Observing summary

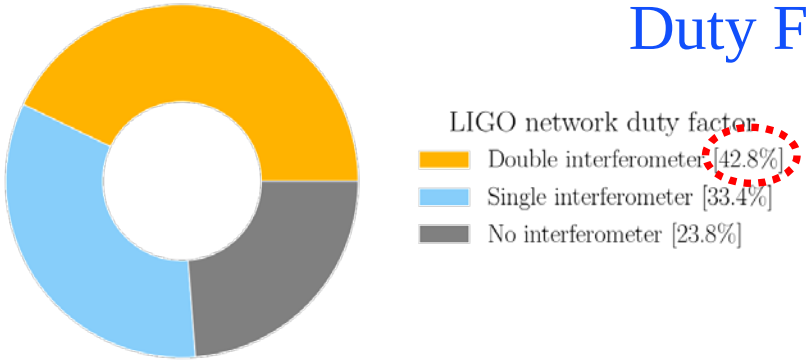
O1

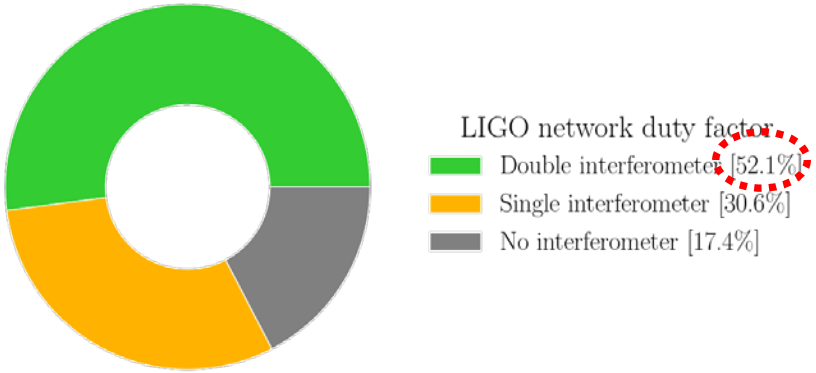
O1, which began at 10:00 am CT on September 18th, 2015. O1 ran for 16 weeks and 4 days and ended January 12th 2016 at 10:00 am CT. Double Interferometer cumulative uptime was 42.8 %.

O2 still in progress

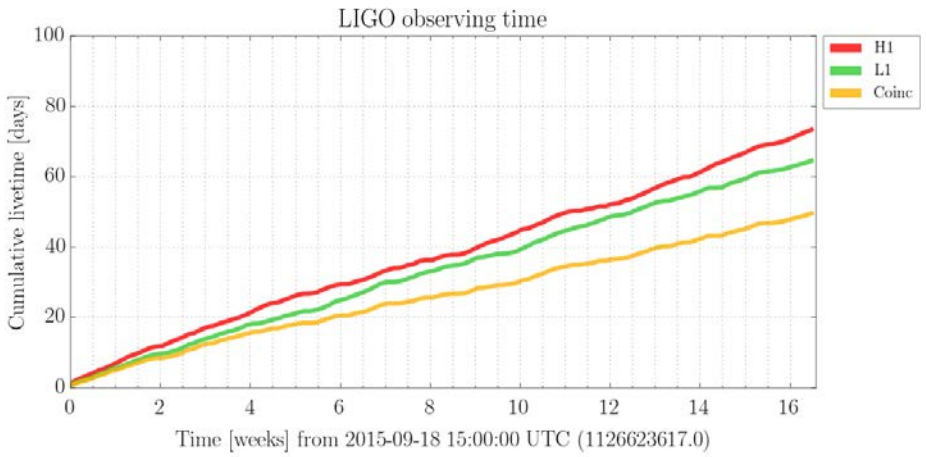
O2 commenced 10:00 am CT Nov 30th 2016. As of Friday April 28th 2017, (21+ weeks or 3270 hours) into O2, Double Interferometer cumulative uptime is around 52.1%.

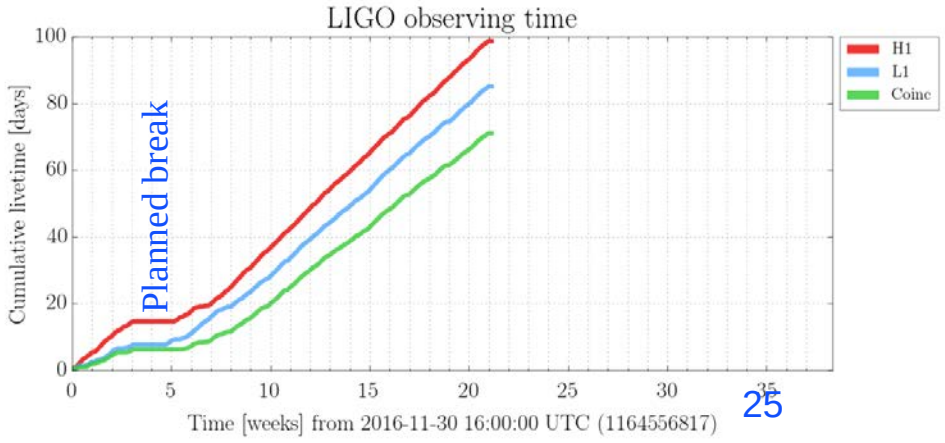
Duty Factor





Total Observing Time

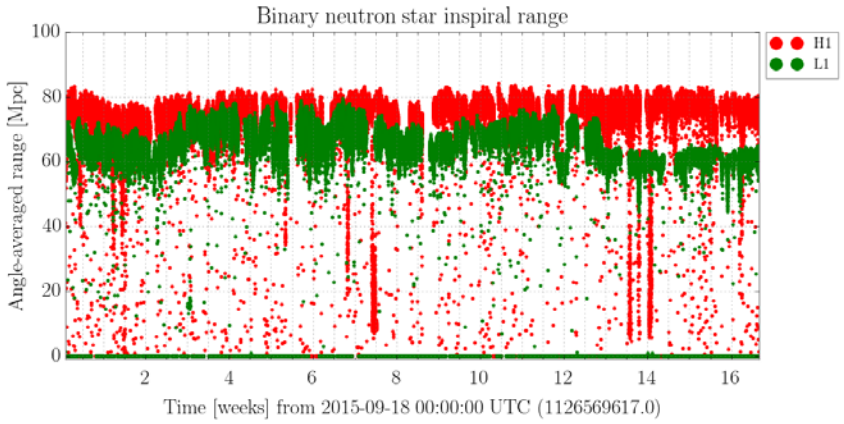


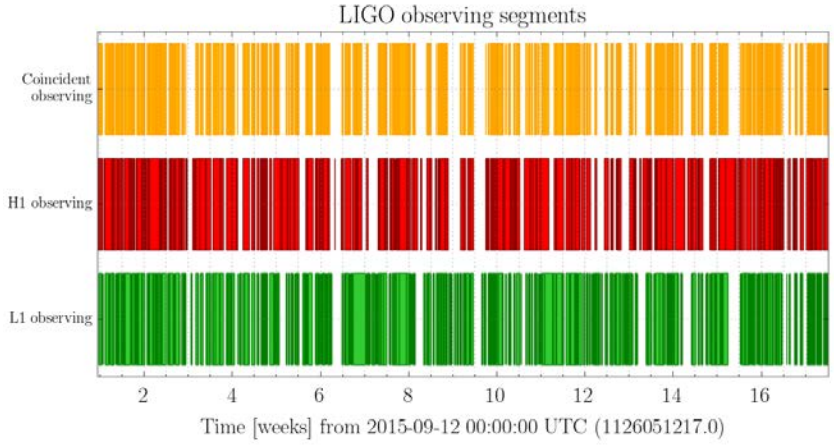


O1 & O2 Performance: Observing summary

O1

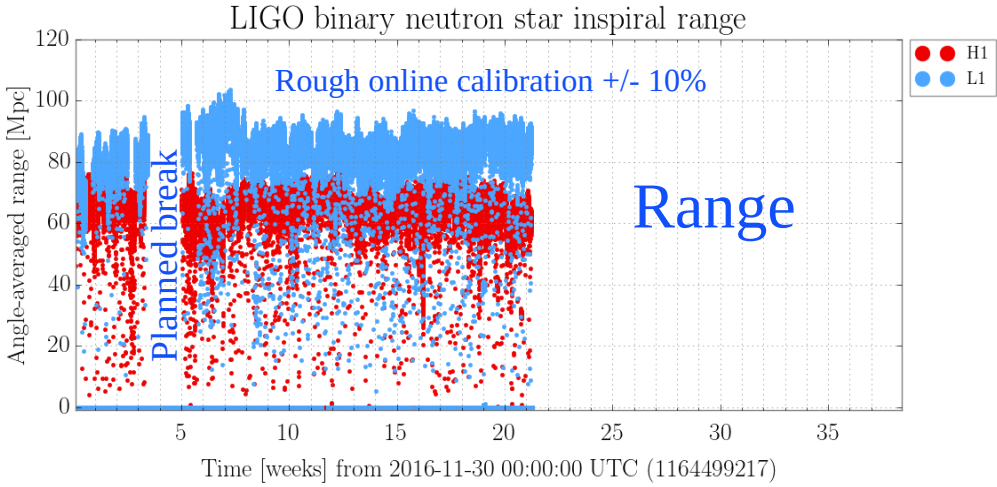
- ***The L1 & H1 detector achieved a NS-NS inspiral range of ~60-80 Mpc during O1***

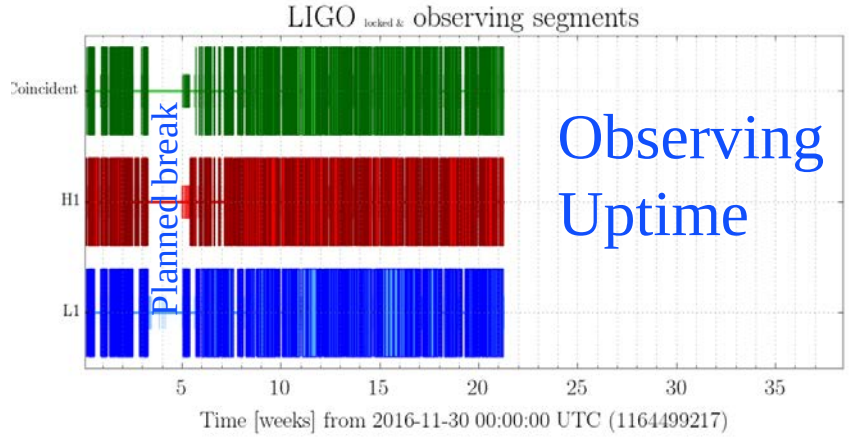




O2 still in progress

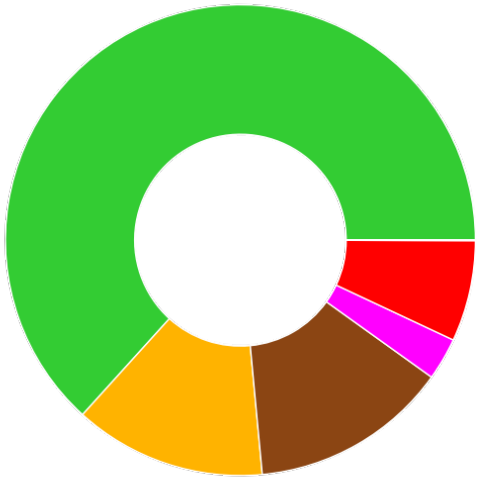
- ***The L1 & H1 detector achieved a NS-NS inspiral range of ~65-95 Mpc during O2***

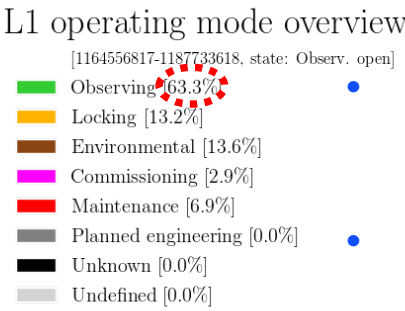




LIGO O2 Operational State and Mode

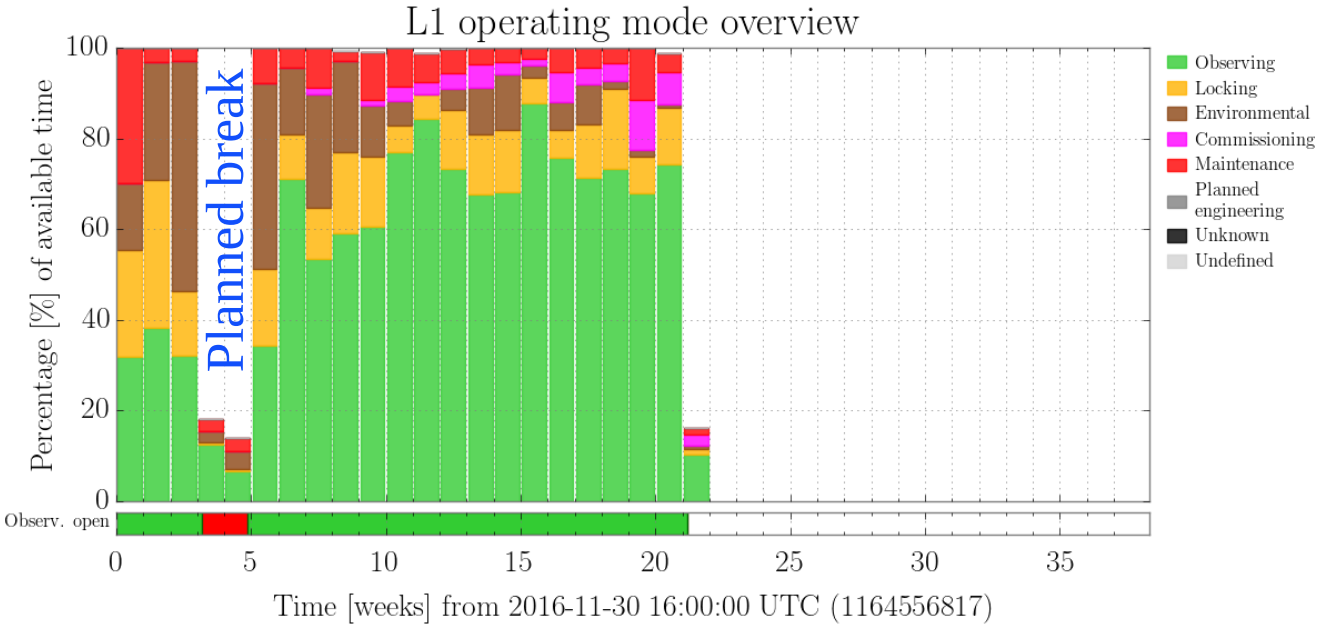
Livingston





- O2 commenced 10:00 am CT Nov 30th 2016. As of Friday, (21+ weeks) into O2, Overall L1 operations has achieved a cumulative uptime of around 63.3%.
- This performance is a little better than expected performance of ~60% and the trend is improving.
- The main cause of down time are **environmental**, **locking**, **preventive maintenance**, **commissioning time** and faults that required **corrective maintenance**.

Operator-reported Top-level modes: Causes of state.



LIGO

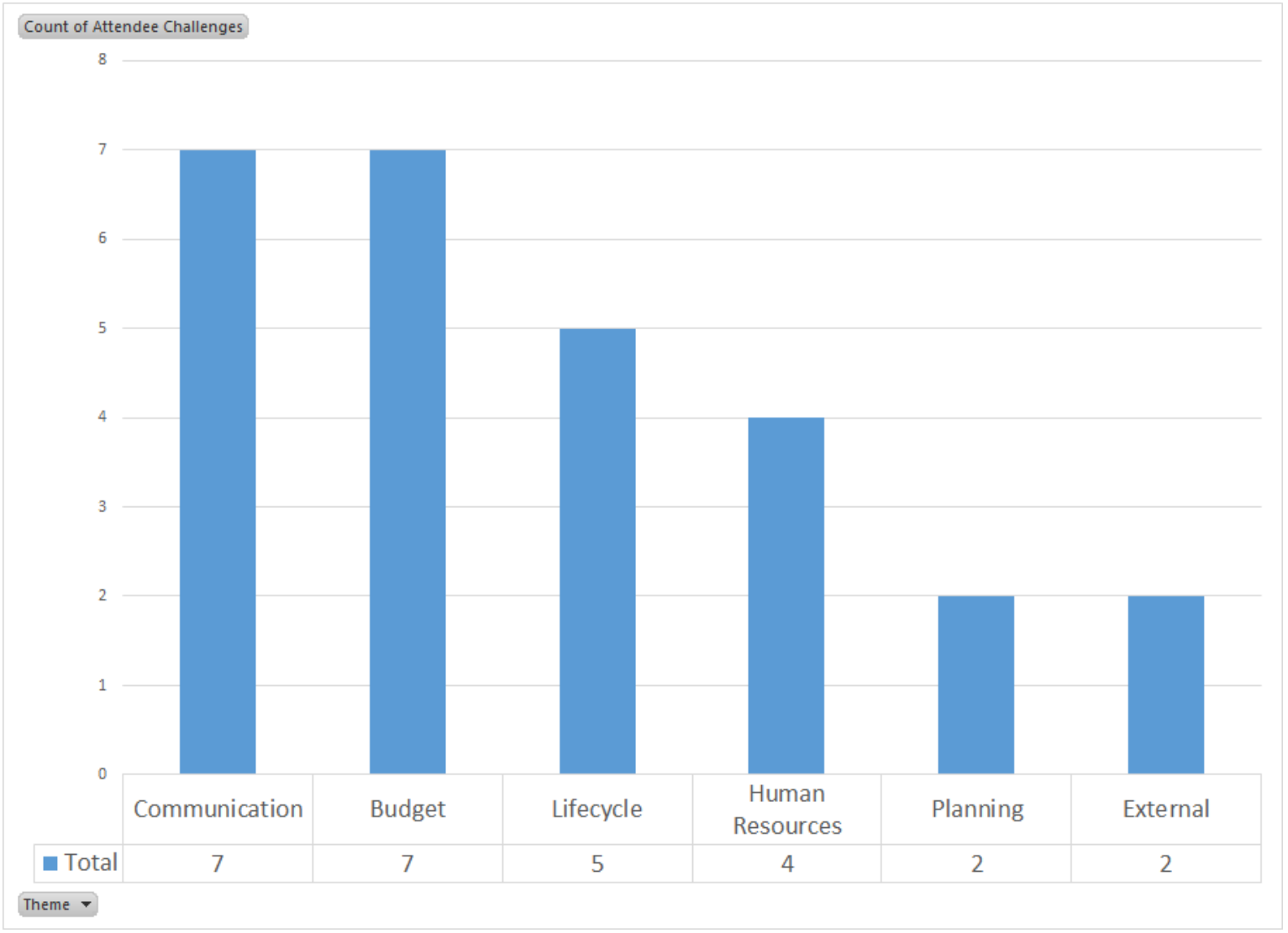
Conclusion

- **LIGO's Operation and Maintenance has been informed by 20 years of observatory site activities, together with robust Lab-wide engineering, systems, business and managerial support.**
- **The Advanced LIGO Project provided a firm foundation of change control, documentation, issue tracking, etc., that remain in use.**
- **We are implementing several modern managerial systems, including computerized maintenance management, tracking performance indicators, quantitative long-term maintenance planning, etc.**
- **The first observational run O1, and the demands place on operations from the detection, were handled successfully.**
- **We are 21+ weeks into O2, which is proceeding well. Many thanks to the amazingly dedicated staff.**

We are 21+ weeks into O2, which is proceeding well. Many thanks to the amazingly dedicated staff.

Thank you!

Round Table Discussion on common challenges to LF O&M



Common communication challenges

Count of Attendee Challenges Theme	Attendee Challenges	Total
Communication	Communication across observatory.	1
	Consistancy in guidance.	1
	Coordination across multiple layers of management.	1
	Developing consistent processes across observatory	1
	Repeat requests for detailed data previously provided.	1
	Terminology inconsistantly applied.	1
	User communities desires shift, even as our protocols sought consistency for changes.	1
Communication Total		7

Common budget challenges

Count of Attendee Challenges Theme	Attendee Challenges	Total
Budget	Aging equipment, high repair costs of obsolete equipment versus higher replacement costs.	1
	Budget uncertainties.	1
	Funding stagnation (flat budget)	1
	Operating while constructing. Not always ready for prime time.	1
	We are not allowed to keep or budget for "reserves". How then do we pay for unexpected failures of major equipment or instrumentation?	1
	We have items of equipment & infrastructer that cost > $250k, but we cannot establish a reserve for when they break. Ideas: A) Allow programs to set aside/establish a reserve bi-annually in the pop budget, or B) NSF create a pool for access by large facilities when a critical item breaks.	1
	We have to spend or budget to zero on the last day of an award. We then start a new award. We then start a new award with no "cushion". Certainly not any "reserves". This is a big problem.	1
Budget Total		7

Common lifecycle challenges

Count of Attendee Challenges Theme	Attendee Challenges	Total
Lifecycle	Aging/outdated equipment.	1
	Challenges stemming from technical needs & limitations.	1
	Cyber infrastructure evolution, i.e. when do software platform upgrades warrant rebuild?	1
	Rapid evolution of software - freeze critical systems?	1
	When we finish and operationalize a facility, some components have 10 years old technology at commissioning. How can NSF fund upgrades early in operationis to avoid early obsolence?	1
Lifecycle Total		5

Common HR challenges

Count of Attendee Challenges Theme	Attendee Challenges	Total
Human Resources	Complete routine work efficiently with limited staff and budget with available skill sets.	1
	Hiring, training and retaining staff to work in remote locations	1
	How do you deal with "problem" personnel in a university environment? Tennured and/or essentially tennured staff.	1
	Lack of succession/backup	1
Human Resources Total		4

Common Planning challenges

Count of Attendee Challenges Theme	Attendee Challenges	Total
Planning	Being really good at being proactive and even better at being reactive when unplanned projects or problems occur.	1
	Plan preventative maintenance and repairs/enhancements around observing work by staff and vendors.	1
Planning Total		2

Common external challenges

Count of Attendee Challenges Theme	Attendee Challenges	Total
External	External partnerships dependencies.	1
	With a continental scale, neon has varied situations - wildfire, floods, migration of protected species, etc., not in our control but impacts performance. Very dynamic.	1
External Total		2