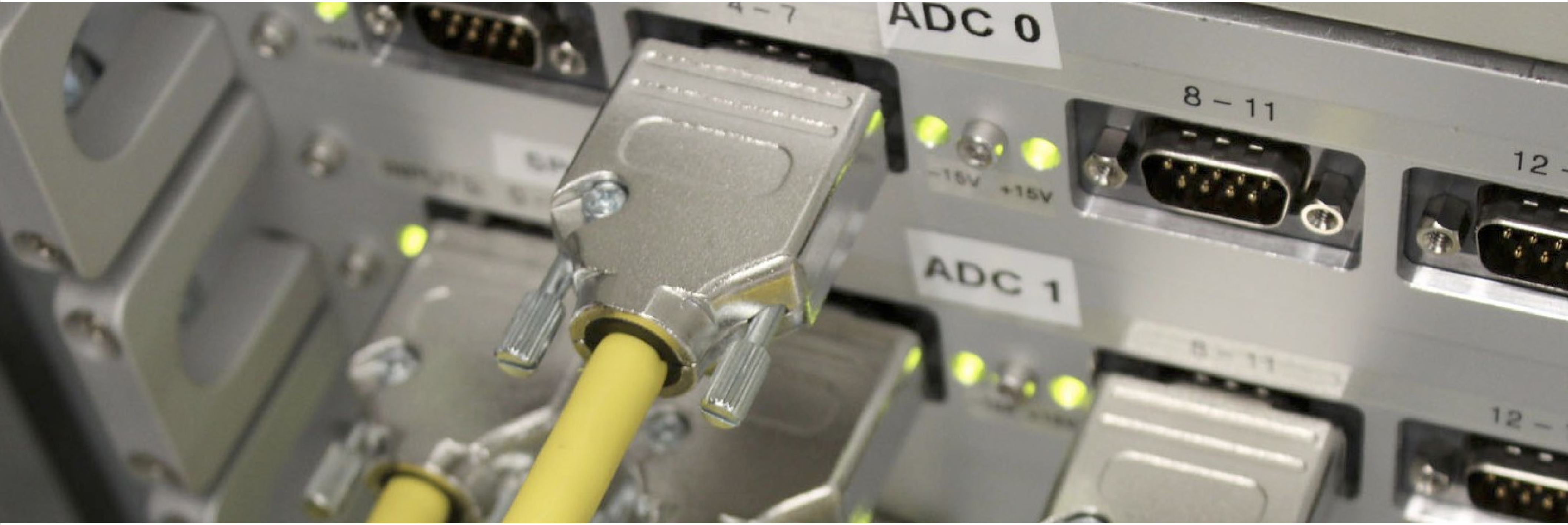
Control of Gravitational Wave detectors



Technical challenges of the Einstein Telescope
15/07/2020

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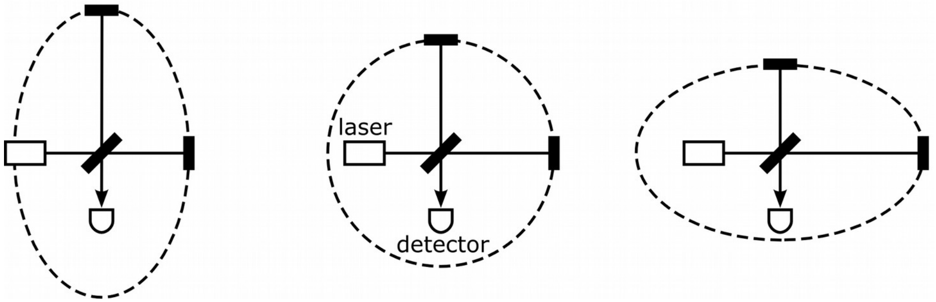
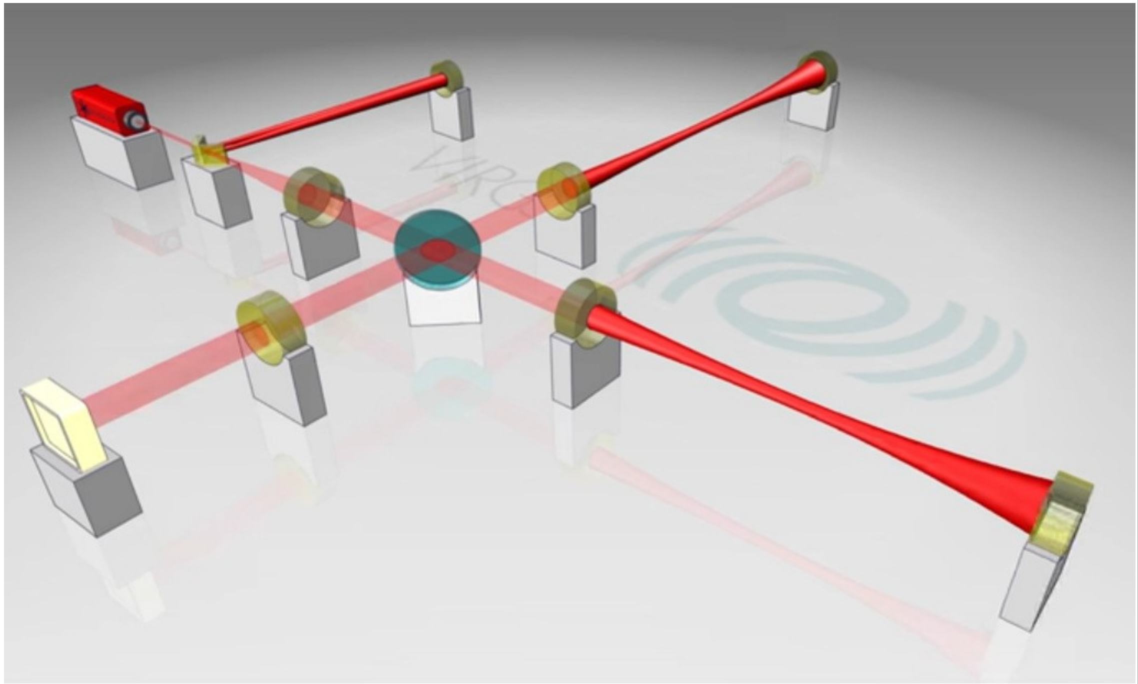
GW interferometers need control





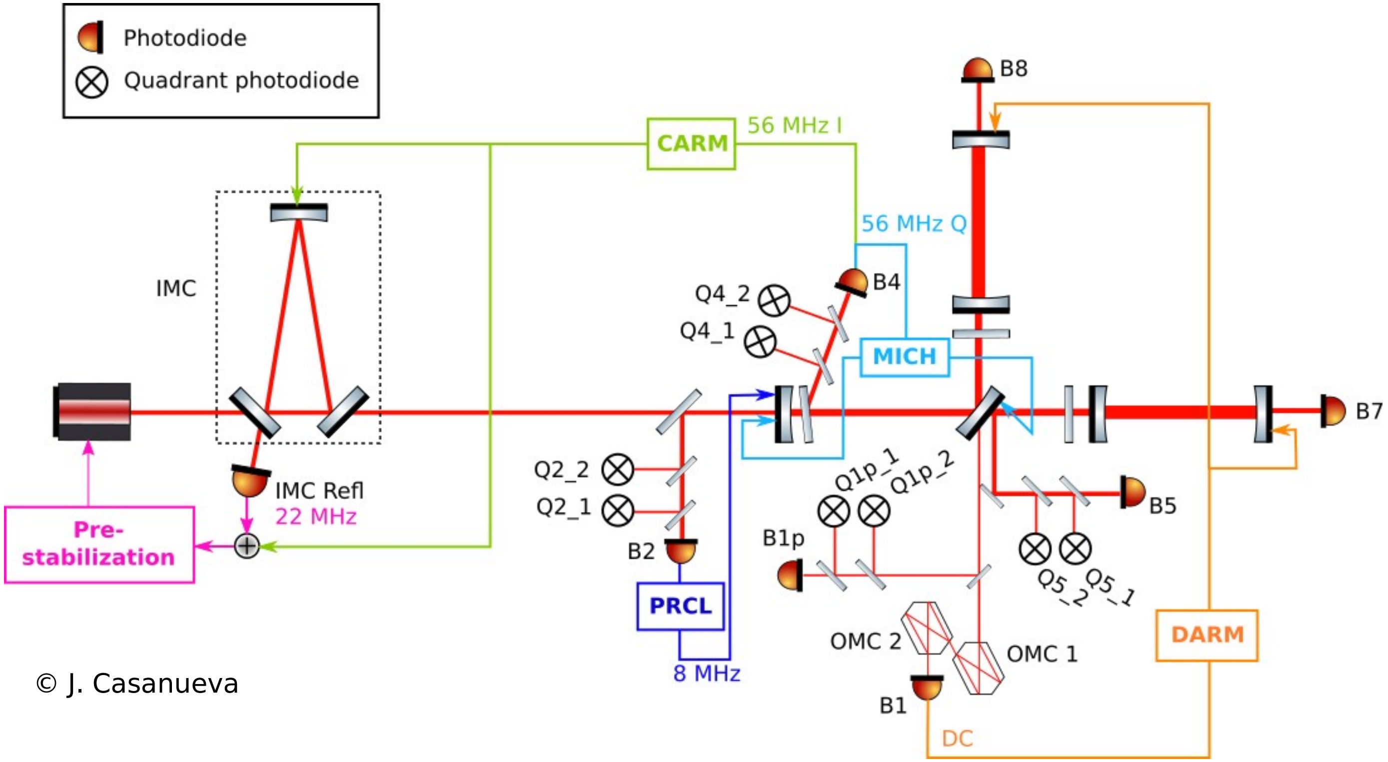
- A passing GW will stretch and squeeze *space-time* in orthogonal directions, typical *strain* of 10^{-21}, equivalent to length measurement with ~10^{-18} m sensitivity over a km!

- Ideal detector is a Michelson interferometer, sensitive to difference of arm lengths

- Practical GW interferometers are complex opto-mechanical systems, sensitivity is increased by using optical cavities (Fabry-Perot), which need to be actively kept on resonance with 10^{-15} meter accuracy

- Real-time control is a key part of measurement scheme, effect of control loops needs to be compensated to obtain calibrated GW signal

Global Control



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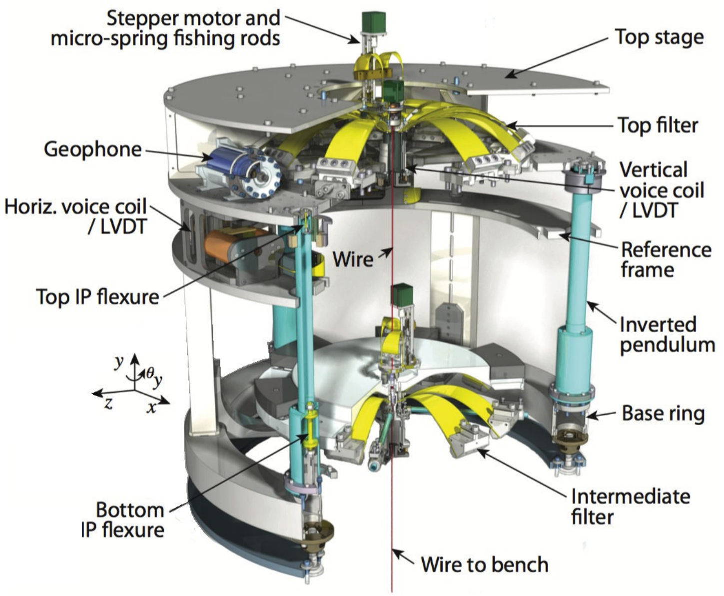
- Cavity lengths are sensed using optical interferometry, which is recorded by (quadrant) photodiodes operating in DC (<10 kHz) or using an RF modulation/demodulation scheme (Pound-Drever-Hall)

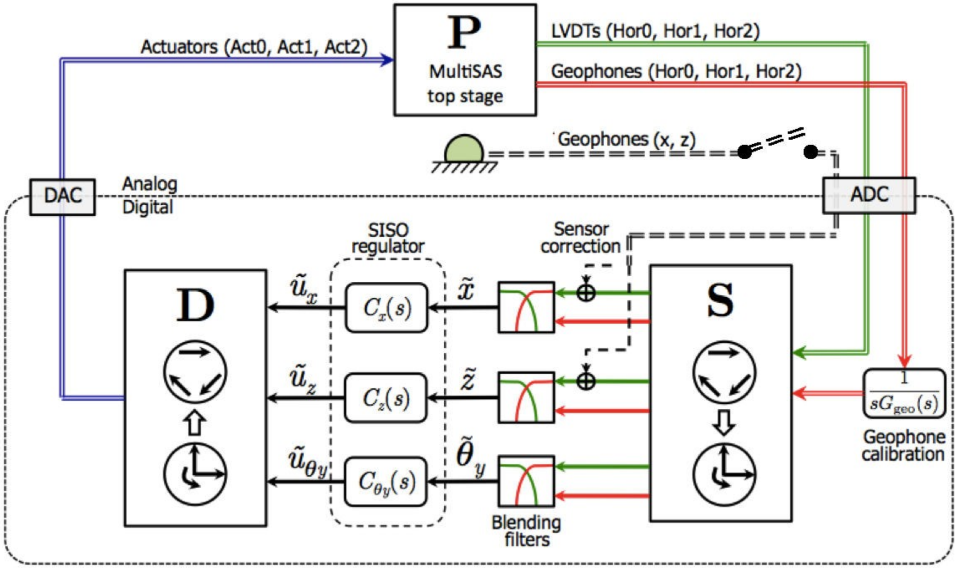
- Cavity lengths are actuated using voice-coil or electrostatic actuators on the mirrors

- **Global control**: control of the complete interferometer, sensor in one place might be used to actuate on mirror far away (20 m for the pathfinder, 10 km for the Einstein Telescope). Typical sample frequency 10 kHz, control bandwidth ~100 Hz

- Apart from controlling distances, also need to control alignment with better than microradian accuracy

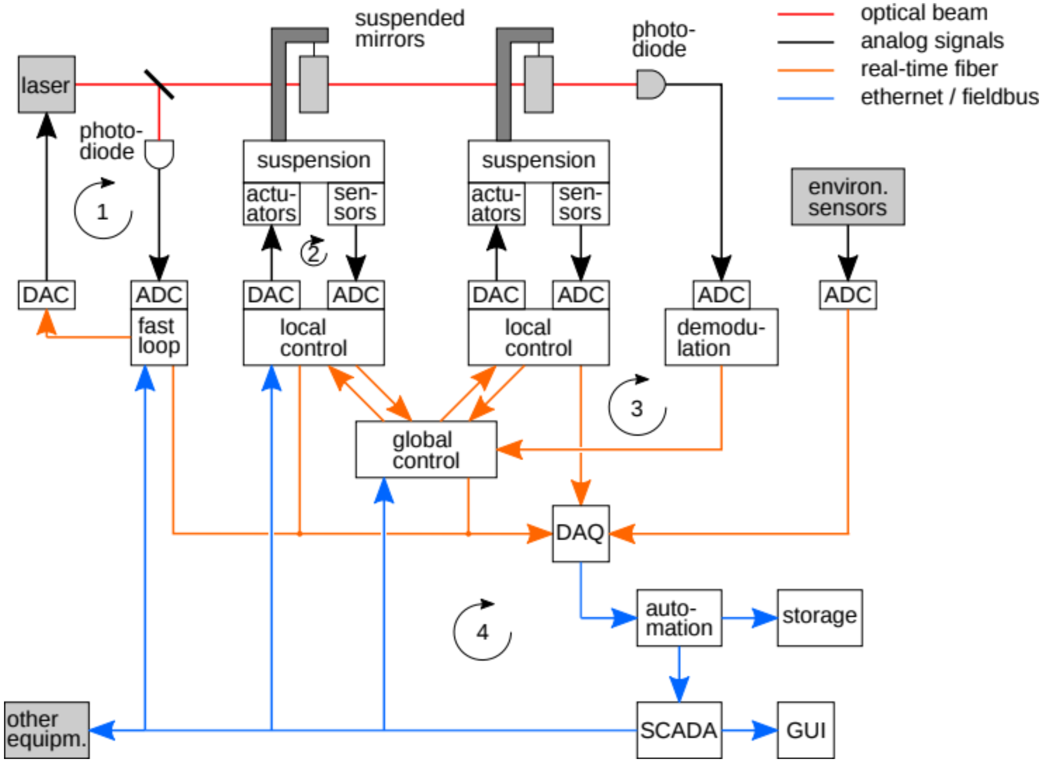
Suspension control

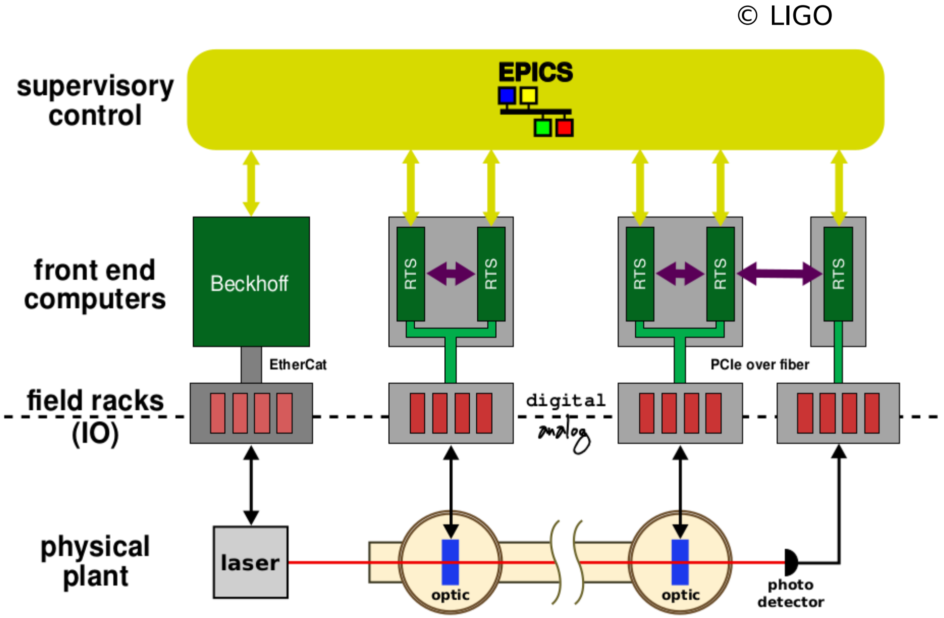




- Mirrors need seismic isolation system with extreme performance: passive attenuation at high frequencies, but active control needed at low frequencies to damp resonant modes
- **Local control**: each mirror suspension is controlled individually (~1 rack of electronics), typically involving 20-30 sensors and 10-20 actuators
- Complicated Multi-Input, Multi-Output (MIMO) systems involving sensor blending (e.g. position sensors with accelerometers), coordinate transformations, minimizing cross-coupling between degrees of freedom, ...
- Typical control bandwidth 1-20 Hz, sample frequency < 10 kHz

Overall control scheme

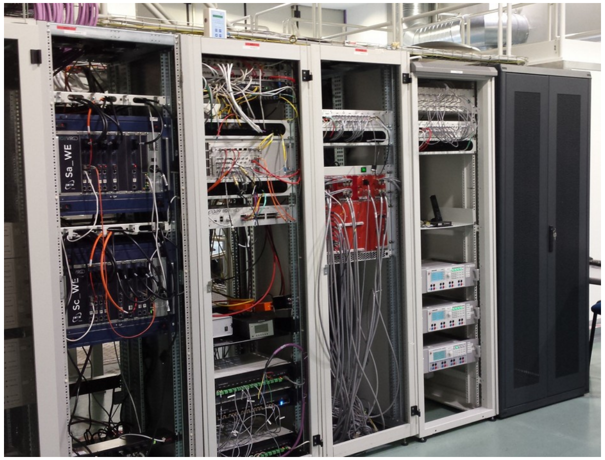


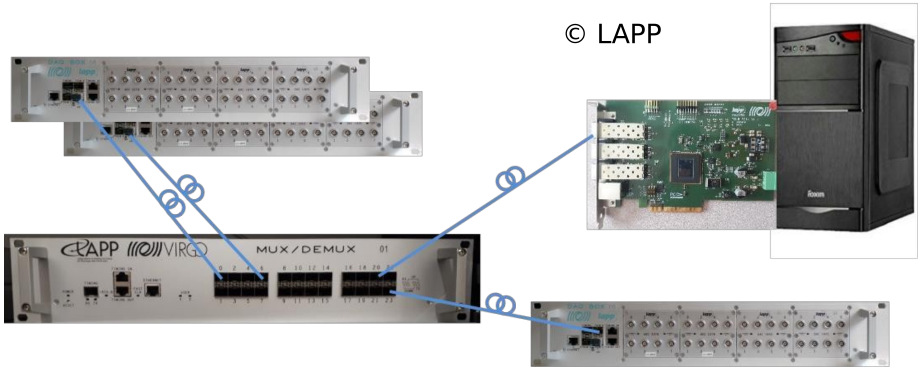


1. Some very fast (~MHz) digital or analog control loops (e.g. laser power and frequency stabilization)
2. Fast (~10 kHz) local control of all mirror suspensions using many sensors and actuators
3. Fast (~10 kHz) global control of whole interferometer, using interferometric sensing
   Distributed control: needs real-time communication network
4. SCADA-type slow control (~1Hz), automation, supervision and user interfaces

All signals are recorded on disk by a DAQ pipeline for debugging and extracting GW signal

Control hardware





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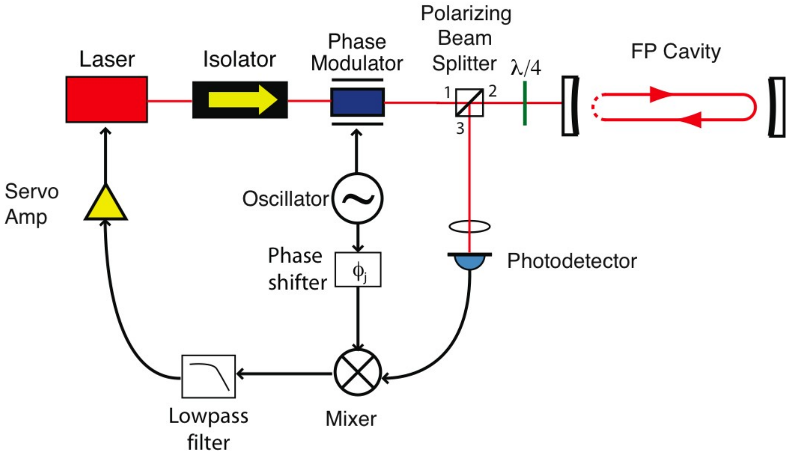
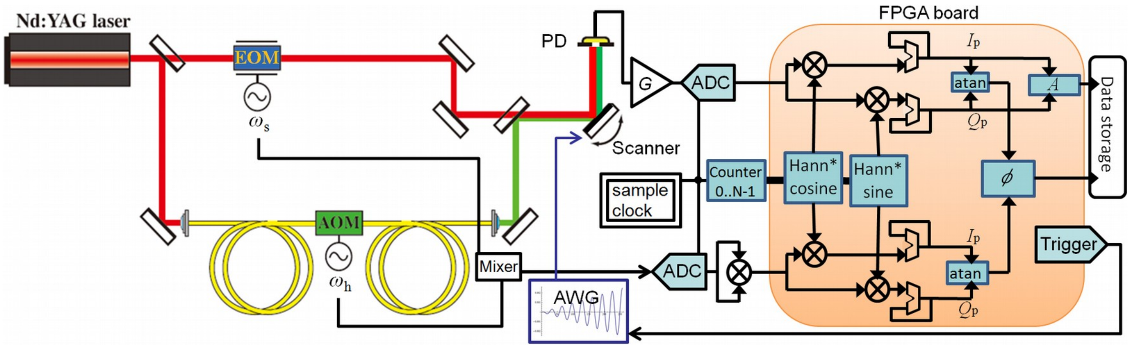
- Historic progression of electronics: analog -> barely working custom digital -> comfortable custom digital -> off-the-shelf
- Current generation: hard real-time digital control consisting of ADCs, DACs and controllers (real-time Linux PCs).
  Typical sample frequency 10-20 kHz, control algorithm programmed by end-user in Simulink or similar
- Distributed system, sensors and actuators separated by kilometers: need real-time fiber communication
  LIGO uses ‘Reflected Memory’ by Dolphin, Virgo uses home built fiber system, maybe >10 Gbit ethernet in future?
- Fastest loops are mostly analog, but some recent examples of digital loops at ~1 MHz
  More flexible, might go completely digital in future
- Various ecosystems for real-time control:
  - commercial (NI, DSpace, ...): off-the-shelve hardware, but standard components not good enough for our most critical control loops. Interfaces tend to be propriety -> vendor lock-in
  - home-built in GW community by Virgo or LIGO (see e.g. https://arxiv.org/abs/2005.00219): does exactly what we need, but costs lot of time to develop, produce and maintain, cannot order new parts on short notice
- Ideally would have a high performance modular system built from off-the-shelf components

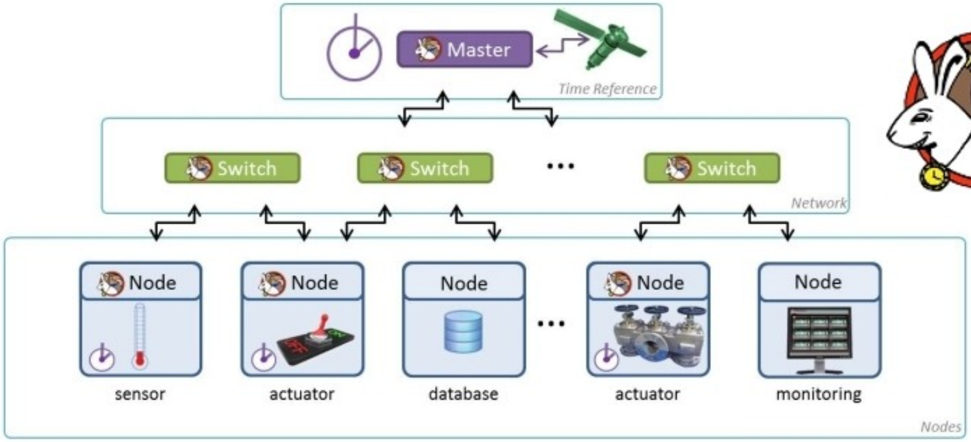
Digital Demodulation





- Main error signals for global control of interferometer are based on an optical modulation/demodulation technique at RF frequencies (1-100 MHz) called Pound-Drever-Hall
  see Eric D. Black, "An introduction to Pound–Drever–Hall laser frequency stabilization", American Journal of Physics 69, 79 (2001)
- Traditionally implemented using analog mixers: not very flexible
- Using fast (~500 MHz @ 14 bit) ADCs and FPGAs, it is now possible to do this digitally
- Some examples:
  - Nikhef's phase camera
    L. v.d. Schaaf et al., J. Phys.: Conf. Ser. 718 072008 (2016)
  - LAPP Annecy demodulation boards used for Advanced Virgo
  - Commercial: MokuLab by Liquid Instruments,
    spin-off company from GW field
    https://liquidinstruments.com/moku-lab/

Timing system

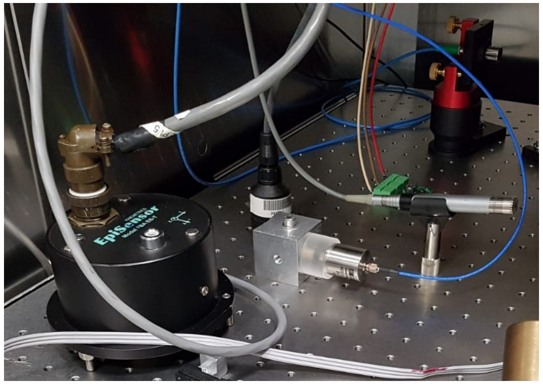


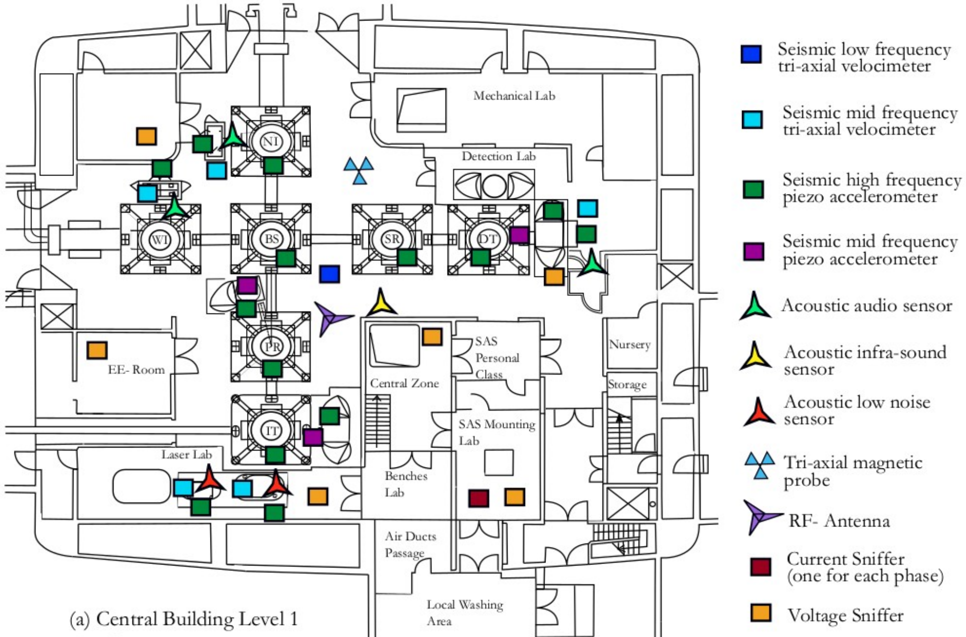
- Need ~microsecond level absolute timing to allow triangulation of astrophysical signals detected by global observatories: synchronize to GPS
- Fast real-time loops distributed over kilometer-scale experiment need to work in perfect synchronization
- Use of very fast (~500 MHz @ 14 bit) ADCs for digital demodulation requires better than picosecond level relative timing jitter between modulation and demodulation signals
- Currently using a custom timing system that distributes IRIG-B and 10/100 MHz signals.
  This works, but some signals are limited by phase noise
- Will in future likely upgrade to White Rabbit timing system: open-source hardware developed at CERN with sub-nanosecond accuracy. Now commercially available from various vendors
  (e.g. OPTN, spin-off of VU Amsterdam)

Low-noise electronics

- Many of our sensors and actuators need careful design of low noise electronics to become limited by fundamental noise sources (e.g. thermal noise, shot noise)
- Signals typically have a very large dynamic range (e.g. lot of control authority needed < 10 Hz, while needing extreme sensitivity > 10 Hz): use complex analog whitening/de-whitening filters to not be limited by quantization noise. ADCs/DACs with more effective bits would help simplifying analog electronics and mechanics (typically 24 bit @ 100 kHz - 1 MHz)
- Some recent examples of electronic noise:
  - main photodiodes were limited by 1/F noise from thick-film resistors
  - magnetic voice-coil actuators on main mirrors are driven by a differential signal. Wasted months of machine time with bad sensitivity before discovering that spurious common mode signal was pushing (slightly charged) mirrors electrostatically
  - slight non-linearity of DACs causing slight amount of noise at sum and difference frequencies of calibration lines
  - cross-talk between neighboring cables
  - noisy switched mode power supplies
  - high harmonic of serial digital communication spoiling RF signals
  - quantization noise of 32 bit floats

Environmental monitoring





(a) Central Building Level 1
Fast Sensor Map

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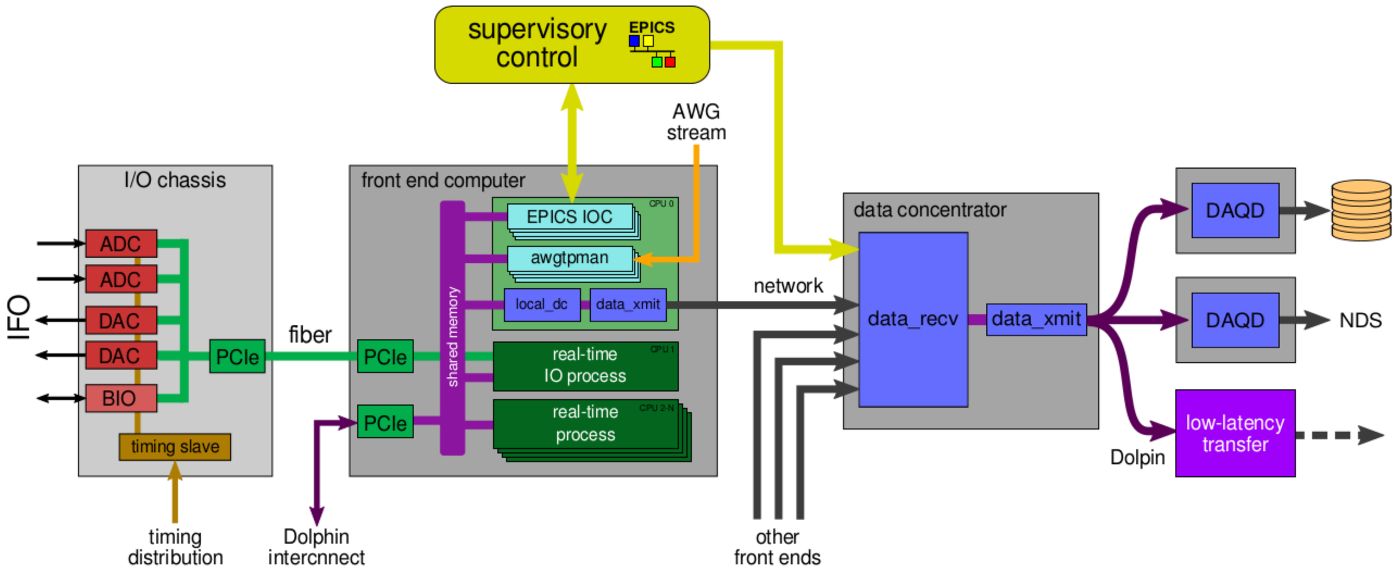
- GW interferometers are the most sensitive instruments ever built
- Need to understand environmental noise coupling and guarantee that our GW signal is not a spurious local disturbance
- Vast array of fast (acoustic, seismic, magnetic, electrical, ...) and slow (temperatures, pressures, meteo, dust, ...) sensors installed throughout the whole experiment
- Also need to inject environmental noise to measure transfer functions: loudspeakers, magnetic coils, shakers ....
- No active R&D, but always interested in low-noise actuators and sensors

Data Acquisition

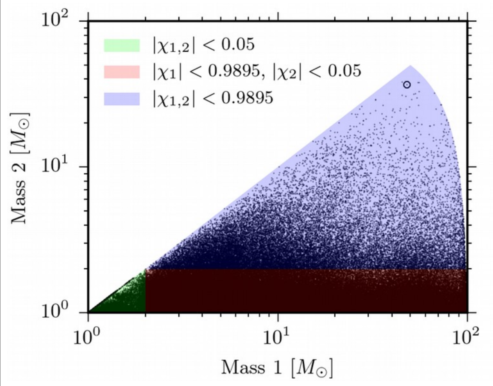


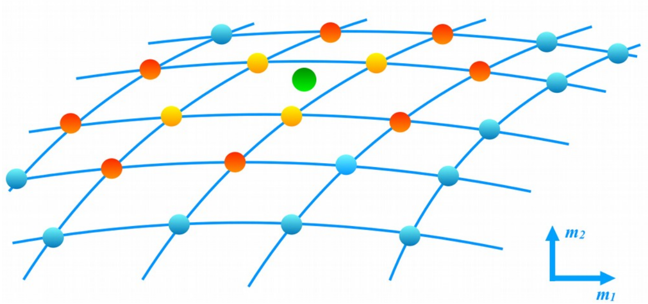
- Science output of a GW interferometer is just a single *strain* signal at ~20 kHz, easily distributed around world with low latency

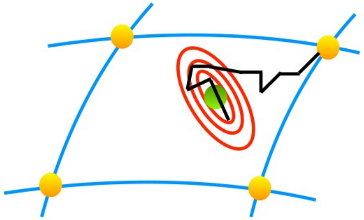
- For debugging and guaranteeing that the signal is real, we store many signals from the interferometer (optics, mechanics, control signals) as well as environmental signals (microphones, seismometers, magnetometers)

- For the Virgo interferometer, we store ~4000 fast channels (~10 kHz) and more than 30000 slower channels (1 Hz), for a total data of ~4 TB/day. A 1-year science run of measuring 24/7 thus needs ~PetaByte storage. Einstein Telescope might have order of magnitude larger data flux

Computing/data analysis







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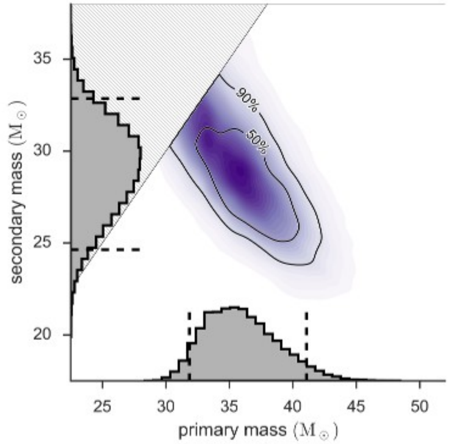

- Several different schemes of offline data analysis
  - inspiraling binary systems (black holes, neutron stars): matched filtering with ~100.000 templates over a grid in large parameter space to detect signal with known signature
  - once signal detected: Monte Carlo style variation to estimate exact parameters
  - ‘continuous waves’ from spinning pulsars: narrow band FFTs over months of data, while compensating for Doppler shift of earth movement
- Also online analysis of signals for sending rapid (within few minute) alerts to optical telescopes
- Most of these problems are ‘embarrassingly parallel’: high-through computing with large clusters Use of GPUs is explored
- Currently detecting 1 event/week. If Einstein telescope is 10x more sensitive, we will detect several events/hour, might become limited by computing. Might need new algorithms (machine learning, ...)