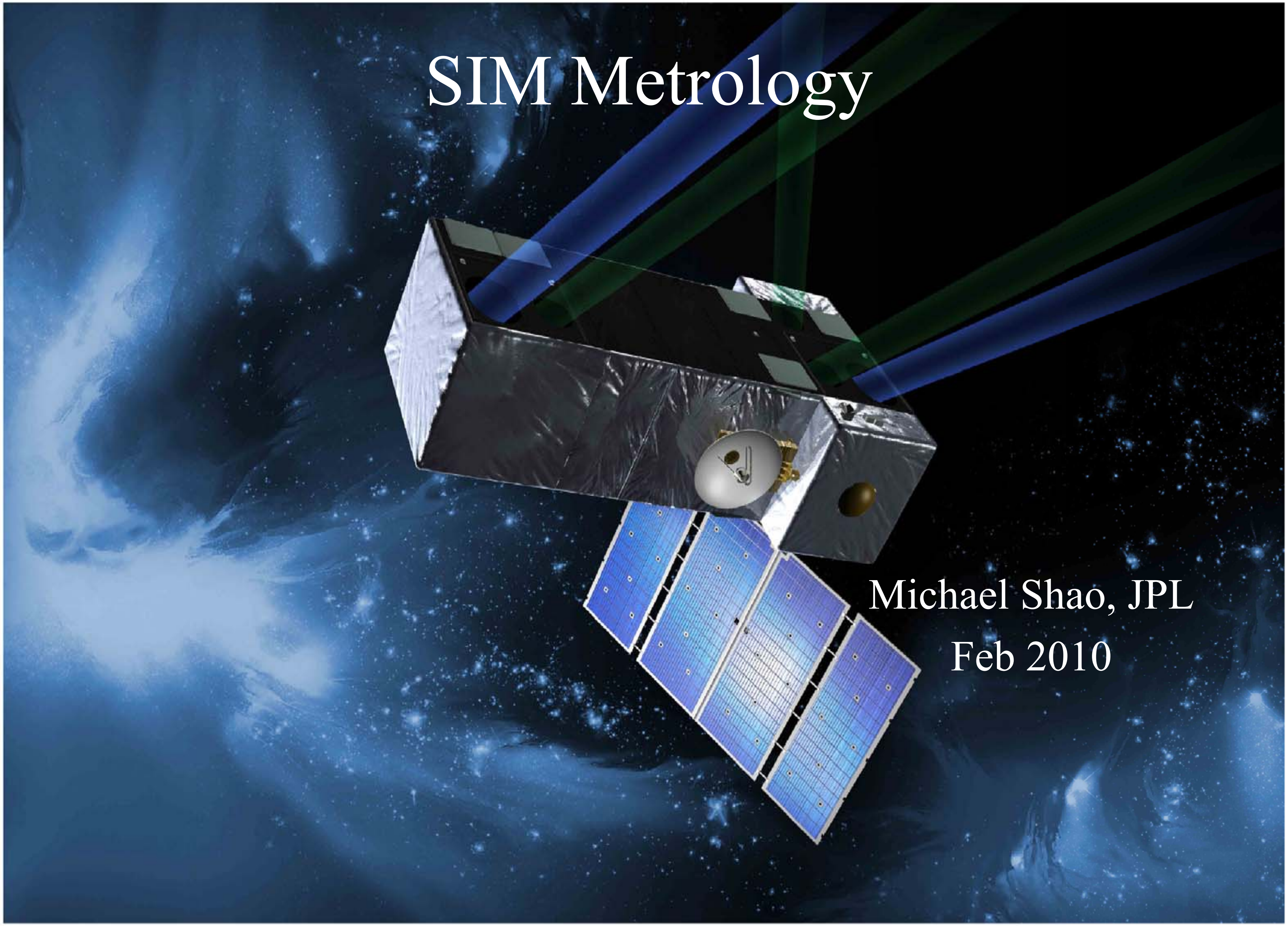
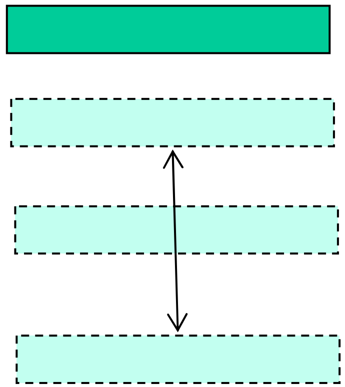

SIM Metrology
Michael Shao, JPL
Feb 2010

Laser Metrology in SIM

- Interferometry vs analog displacement sensors
- Basic heterodyne interferometer concept
- Laser source
- Laser gauge
- Phase meter (electronics)

Laser Interferometry and Analog Displacement Sensors

Analog Sensor
(cap sensor,
Strain gauge
Diff transformer
Etc.)



0-1cm motion
0-1V output

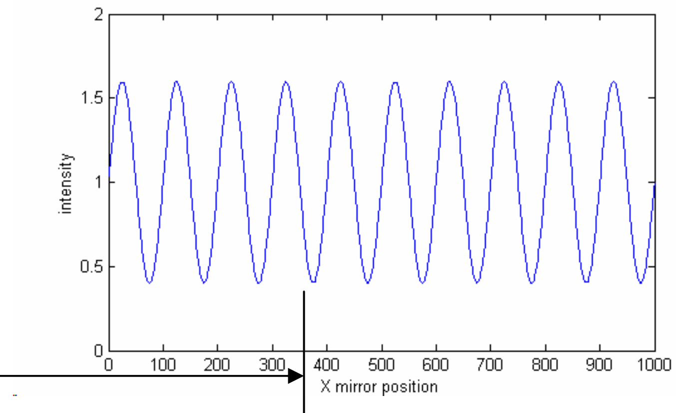
10^{-10} cm precision implies 100pv noise
10^{10} SNR

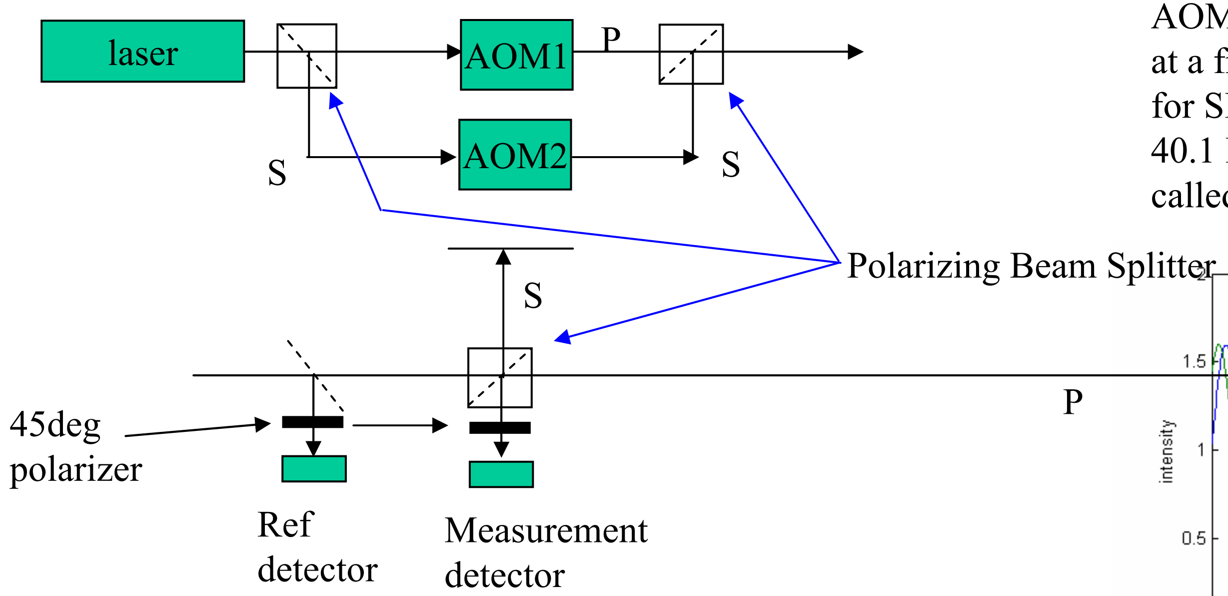
- Laser interferometer is a part analog, part digital sensor.
- For motions > λ, it counts fringes, a digital sensor
- For motions < λ it's an analog sensor.
- If the "standoff" distance is 10mm the needed analog SNR for a laser is 10,000 times lower if λ=1um.
- For SIM precision = accuracy
- 1m motion measured to 10^{-12}

Heterodyne Interferometry

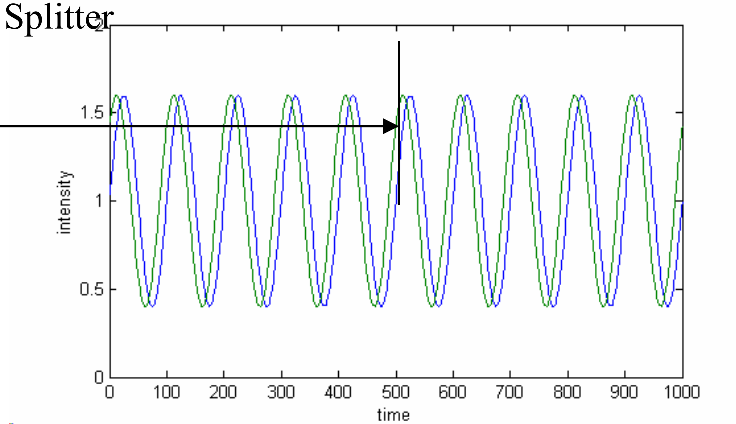
for distance measurement

- Michelson interferometer vs heterodyne interferometer



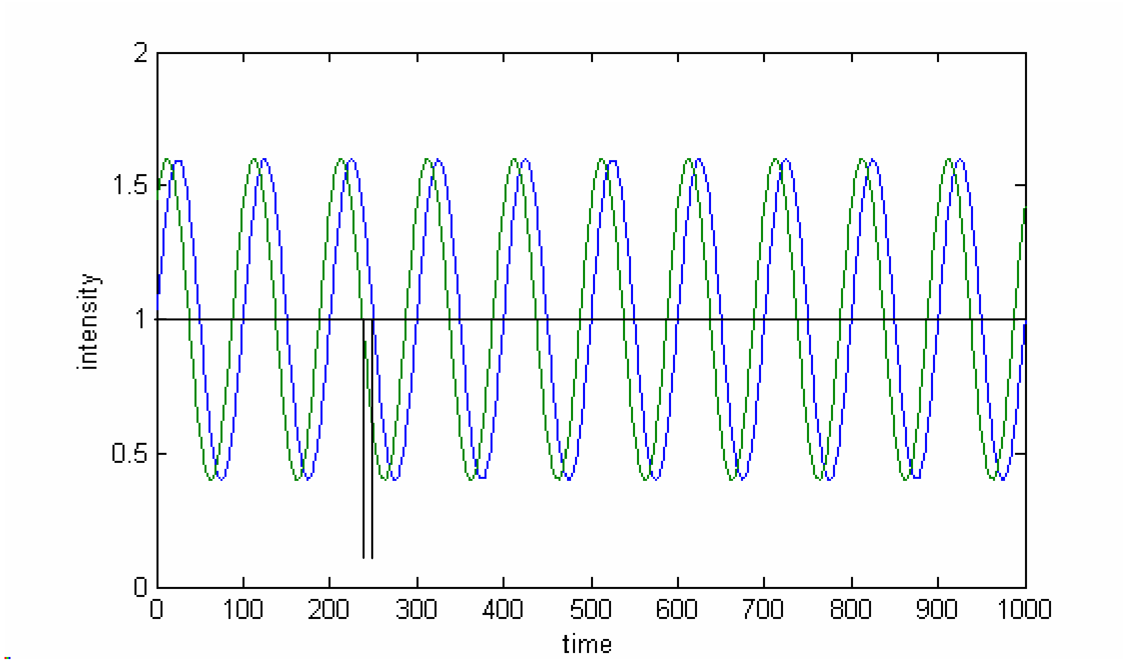


AOM's are freq shifters, a 1um laser is at a freq of 300 Thz. The freq shifters for SIM shift the freq by 40 Mhz and 40.1 Mhz. The diff freq 10~100 Khz is called the heterodyne freq.



Advantages of Heterodyne Interferometry

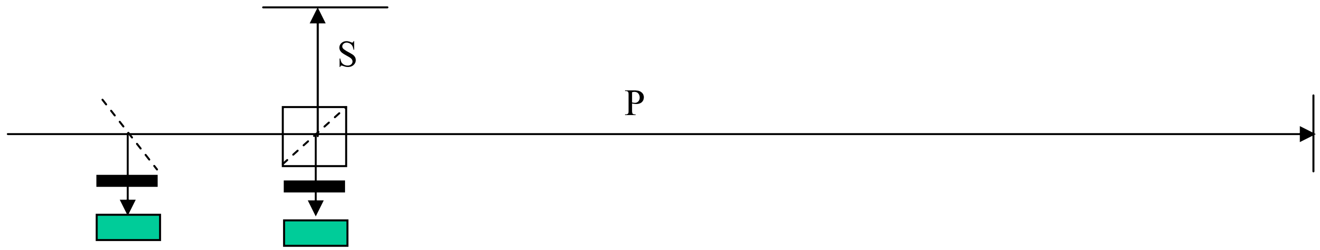
- Signal is AC, mostly immune to dc room light, 60hz flicker etc.
  - Relaxed calibration of DC levels and gain of detector/amp
- Turns length measurement into a time measurement



Time delay measured with high speed clock.
10Khz het-freq, & 500Mhz high speed clock means
the signal is digitized to $\lambda/50,000$

Systematic Errors

- The polarization based heterodyne interferometer was commercially introduced by Hewlett Packard (now Agilent Corp) in the 1980's? It is widely used in the semi-conductor fab industry. However it has relatively large systematic (cyclic) errors (~ $\lambda/200$) that arise because of imperfect polarization components (or improperly aligned components)

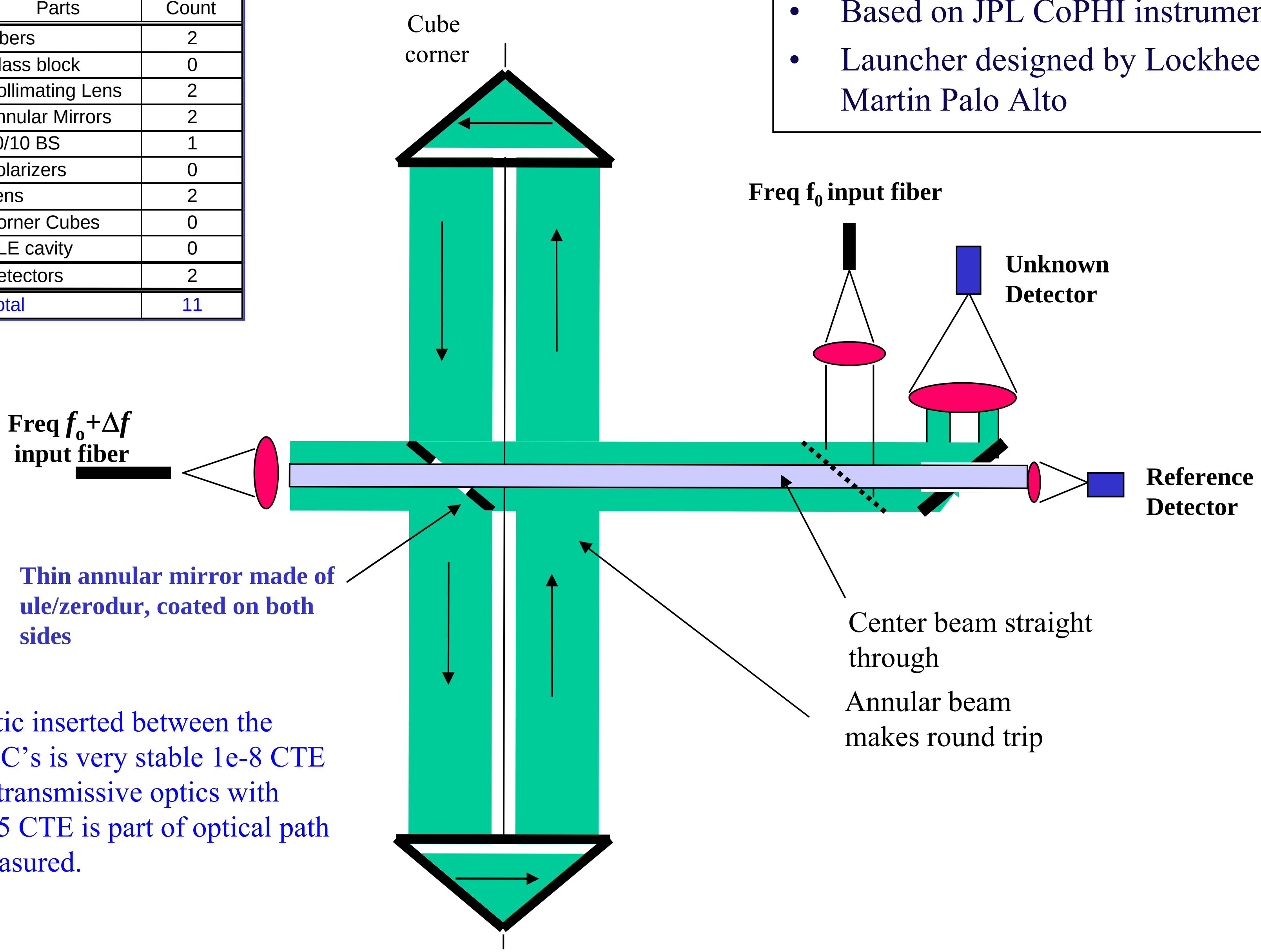


- On SIM we've adopted the spatially separated beam launcher laser gauge. This gauge comes in a variety of configurations.
  - Gauge measures difference in OPD between 2 arms of a stellar interferometer,
  - Gauge measures the distance between two optical fiducials, with the gauge between the two fiducials.
  - Gauge measures the distance between two optical fiducials, with the gauge outside the two fiducials.

Spatially Separated Heterodyne Gauge

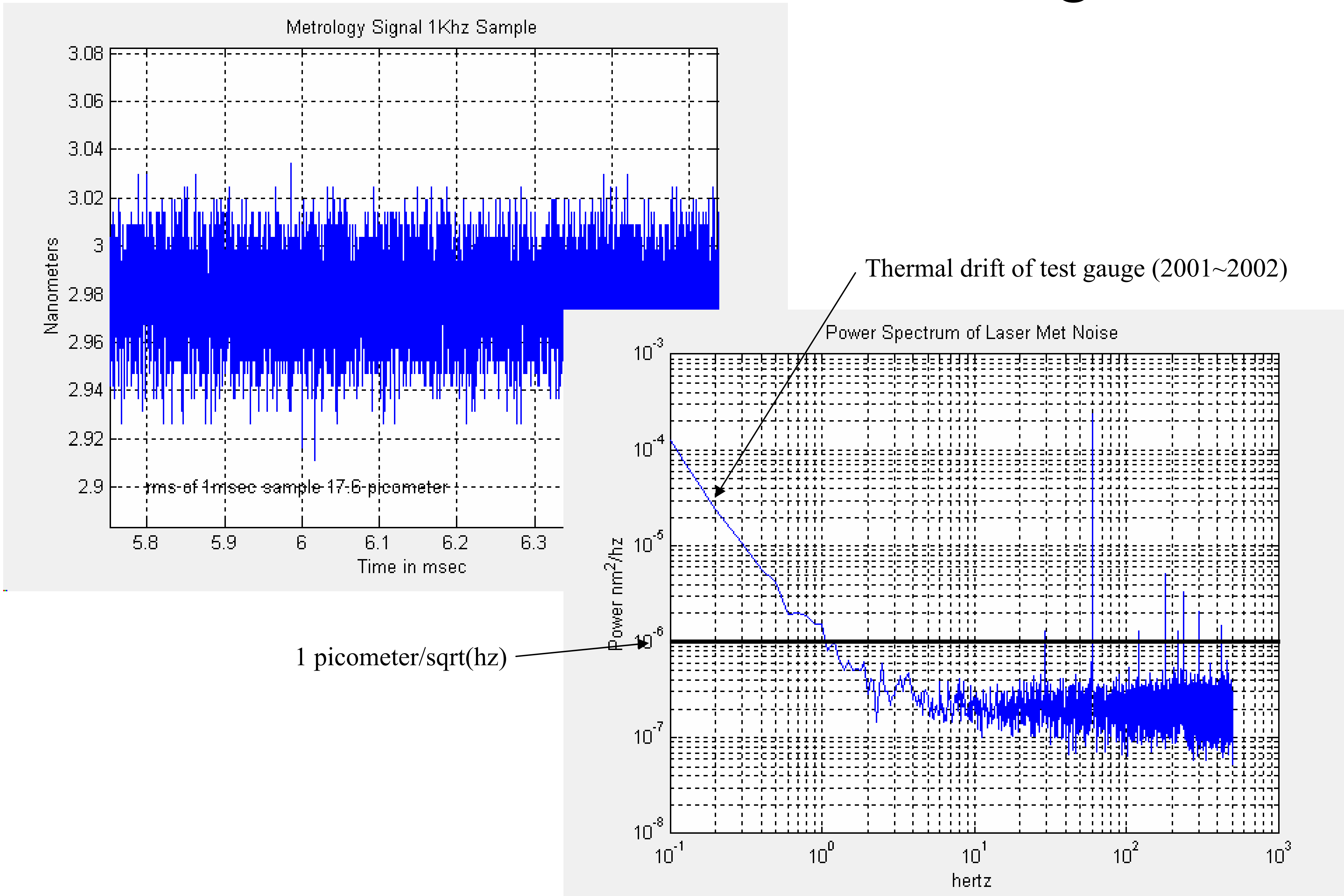
Parts	Count
Fibers	2
Glass block	0
Collimating Lens	2
Annular Mirrors	2
90/10 BS	1
Polarizers	0
Lens	2
Corner Cubes	0
ULE cavity	0
Detectors	2
Total	11

- Based on JPL CoPHI instrument
- Launcher designed by Lockheed-Martin Palo Alto



Optic inserted between the 1 CC's is very stable 1e-8 CTE no transmissive optics with 1e-5 CTE is part of optical path Measured.

SIM Laser Gauge Noise



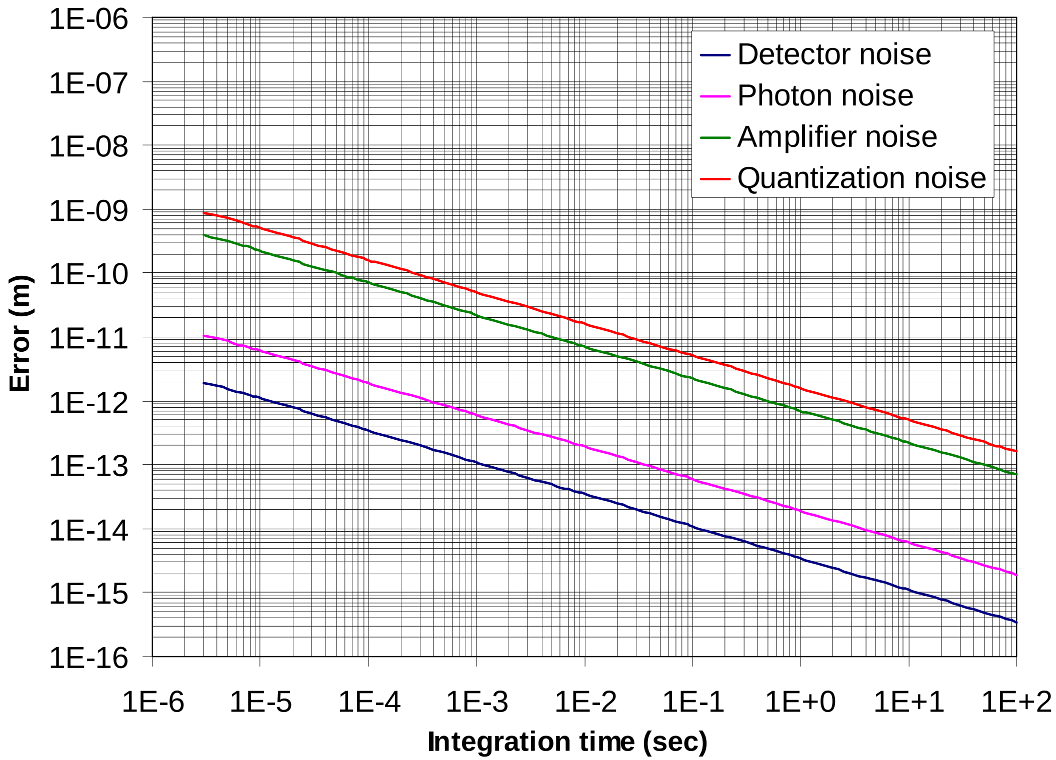
Random Noise Sources (SIM Internal Gauge)

Detector noise	$\varepsilon = \lambda \cdot NEP \cdot \frac{\sqrt{B}}{4\pi\eta P}$
Photon noise	$\varepsilon = \frac{1}{4\pi}\sqrt{\frac{2hc\lambda B}{\eta P}}$
Amplifier noise	$\varepsilon = \frac{\lambda}{2\pi}\frac{\sqrt{4kTRB}}{\eta PR}$
Phase meter quantization noise	$\varepsilon = \frac{\lambda}{\sqrt{12}}\frac{f_{het}}{f_{clock}}$

- P=200nW
- NEP=5x10^{-15} W/sqrt(Hz),
- R=100kΩ,
- heterodyne f_{het}=300kHz,
- clock f_{clock}=128MHz,
- bandwidth B=540kHz,

- Use higher laser power
- Use lower heterodyne frequency
- Use longer integration time (averaging)

$$\langle \delta x \rangle = \frac{\varepsilon}{\sqrt{N}} = \frac{\varepsilon}{\sqrt{f_h \tau}}$$

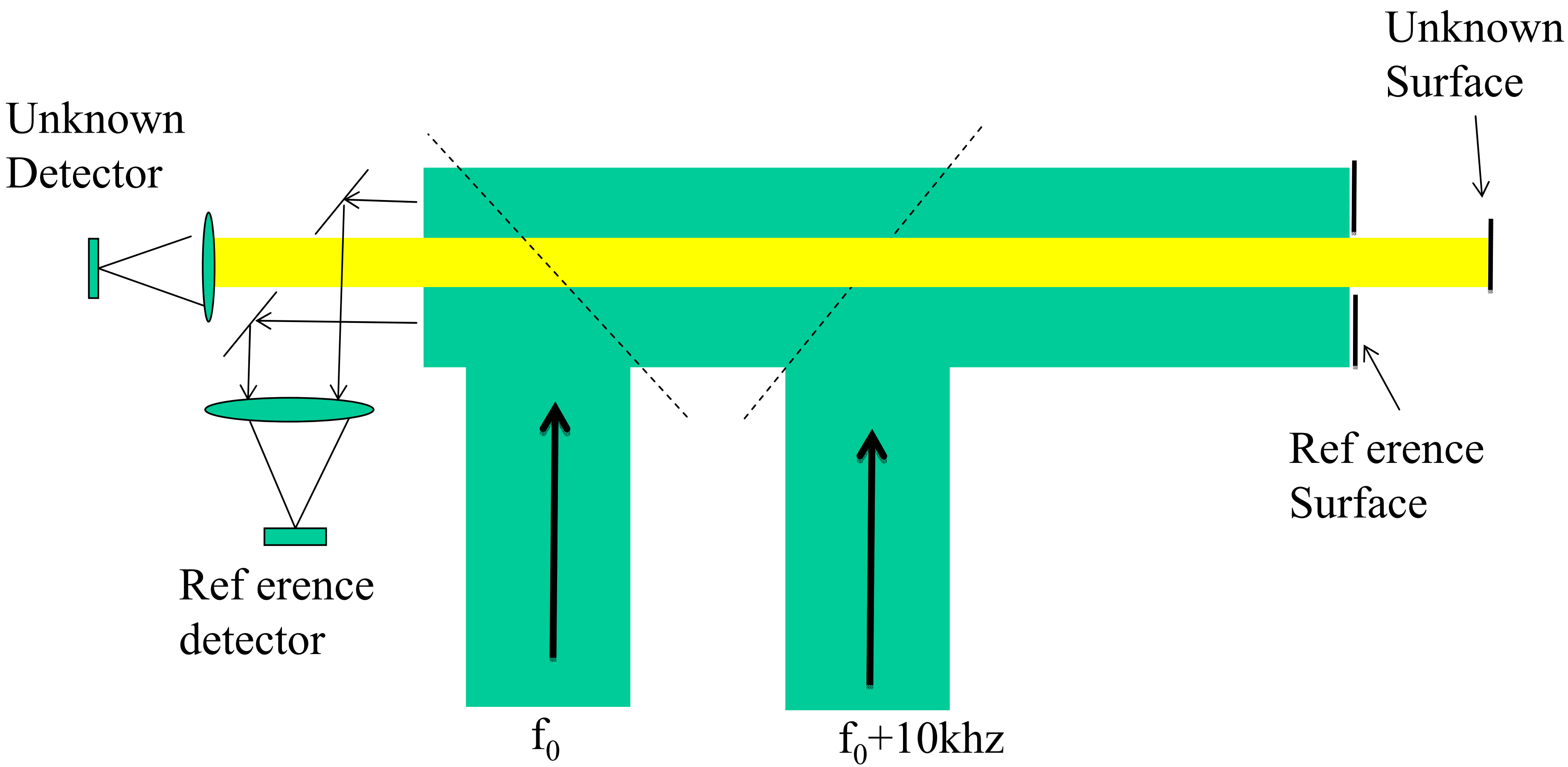


Optimizing Laser Met for a Diff App

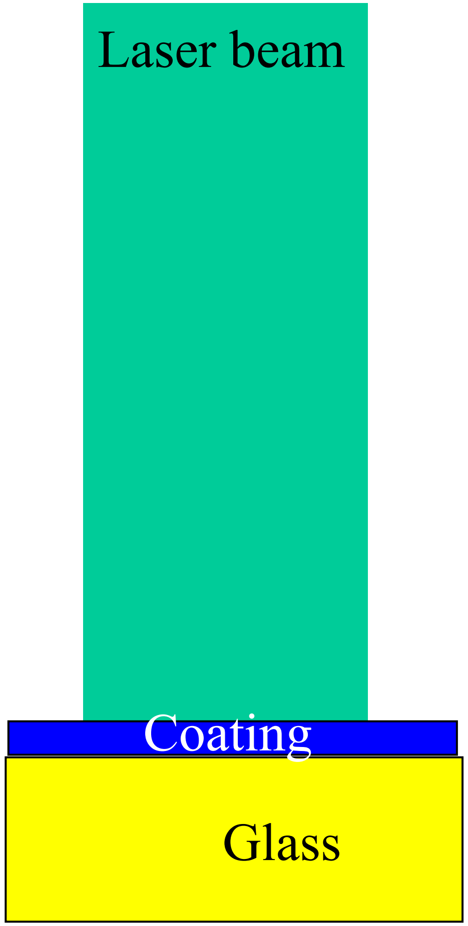
- Phase meter quantization noise (equiv A/D converter noise)
  - _ λ/sqrt(12) *(f_het/f_clock)/sqrt(f_het) ~ 0.6 pm/sqrt(hz)
    - 1.06um, f_het=300Khz,f_c=256Mhz.
  - Change f_het = 10Khz noise ~ 0.12 pm/sqrt(hz)
  - Change f_clock to 512Mhz 0.06 pm/sqrt(hz)
- Laser power
  - Higher laser power reduces detector noise, amp noise, phot noise
  - SIM is amp noise limited. @ 300Khz, R_f~1e5 ohms and an FET opamp with 10nv/rthz noise is equiv to a detector with 1e-13 W/rthz. DC Laser power of 3e-7 W would produce an AC signal equiv to 1e-7W, with a SNR=1e6 in 1 sec. ~0.2 pm/sqrt(hz)
  - Photon noise from a 0.1uW signal is ~0.1 pm/sqrt(hz)
  - Photon noise dominates when laser power exceeds ~ 1 uW.
- Current phase meter is equiv to a 1 Bit A/D running at f_clock. Higher performance will need a high speed multibit A/D converter sampling the sine wave

Other Types of Beam Launchers

- The prior laser gauge was configured to measure the distance between two CC's by inserting optics in between the two CC's.
- An alternate configuration is one where the gauges is external to the two optical fiducials (most useful for GG)



What Does A Laser Measure?



- A laser beam bounces off the reflecting surface of a mirror.
  - Metal ~50nm penetration
  - Dielectric a few microns
- What is the thermal noise is the position of the coating? Brownian motion of the atoms in the reflecting layer. (does the material have to be cooled?)
- At 1 picometer/sqrt(hz) this is not an issue for SIM metrology. But it is a limiting factor for projects like LIGO, or ultra stable lasers that use FP-cavities as short term freq references
- Short answer brownian motion of the coating produces < 10^{-16}m/sqrt(hz) of noise @300K.

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Subhertz linewidth diode lasers by stabilization to vibrationally and thermally compensated ultralow-expansion glass Fabry-Pérot cavities

J. Alnis,[1,*] A. Matveev,[1,2] N. Kolachevsky,[1,2] Th. Udem,[1] and T. W. Hänsch[1]
[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[2]*P.N. Lebedev Physics Institute, Leninsky pr. 53, 119991 Moscow, Russia*

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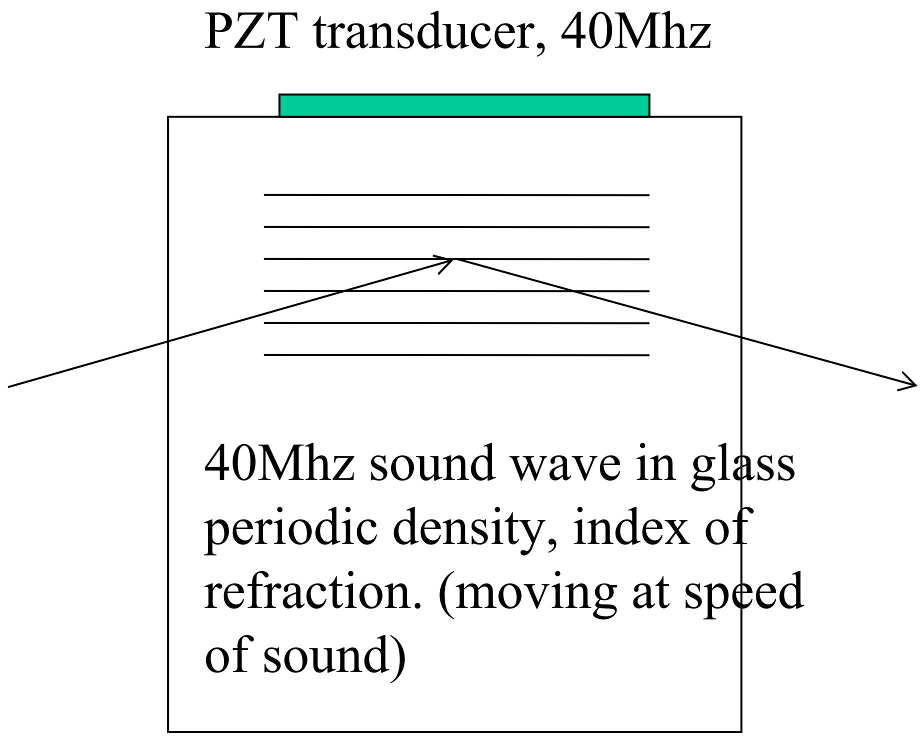
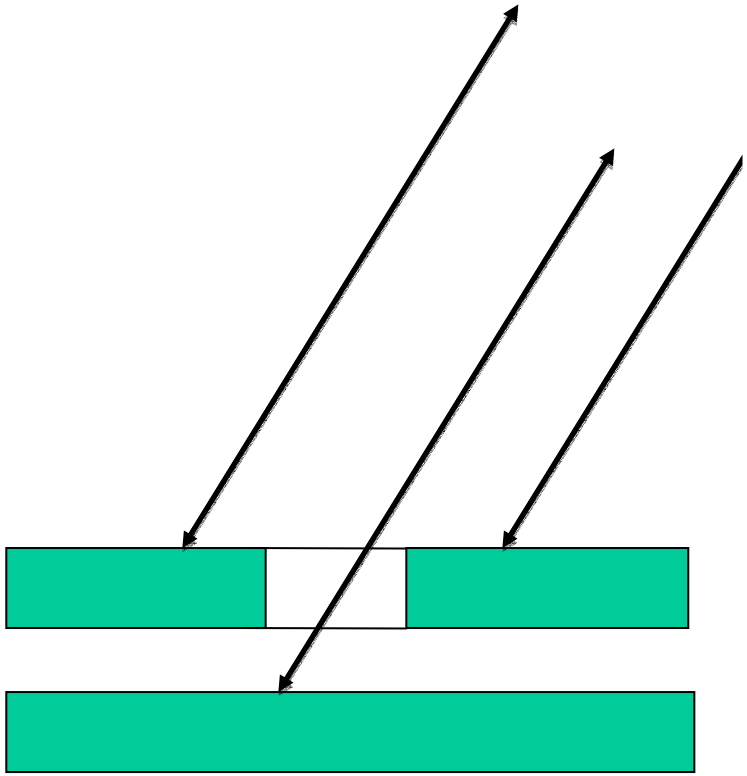
AO Freq Shifters (how they work)



- A laser beam entering a region with a periodic variation in will undergo bragg diffraction.
  - diff angle ~ RF freq
  - Freq shift = RF freq.
- Freq shift occurs because the bragg grating is moving (at the speed of sound in glass)
- If the RF signal consists of 2 tones 40, and 41Mhz the diffraction pattern at the output will be 2 beams.
- AOM's are also used as spectrum analyzers. Takes an instantenous fourier transform of the input RF signal.

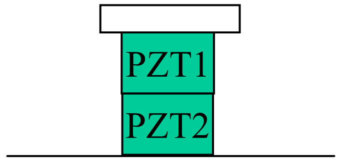
Possible Configuration for GG

- 1st thoughts, maybe revised (at 100% level) after discussion in Pisa.
- Measure all 6 DOF of the inner cylinder wrt the outer cylinder.
- Using the "external launcher" configuration
  - Outer cylinder has a hole that lets the laser through to the inner cylinder.
  - Both cylinders have special areas that reflect the beam back to the gauge.
    - Several possibilities
    - Most exotic are holographic gratings that can be applied on an arbitrary shaped surface to reflect the laser light 180deg.



Example of What's Done During Engineering Risk Reduction

- Lifetime testing. Class A/B missions have a requirement that mechanisms have a 99.7% probability of working throughout the mission (5yrs) AND there is a backup.
  - Eg a PZT actuator will be designed with 2PZTs
  - Laser lifetime.



- The laser used for metrology on SIM is a diode pumped YAG laser (NPRO geometry). Producing ~250mw of 1.319um output. The lifetime limiting component are the pump laser diodes. It is not possible to achieve 99.7% prob that a single pump diode would last 5.5yrs. Several schemes using multiple pump diodes were investigated.
- Most of the other engineering tasks had to do with building the components to survive launch and work in space.