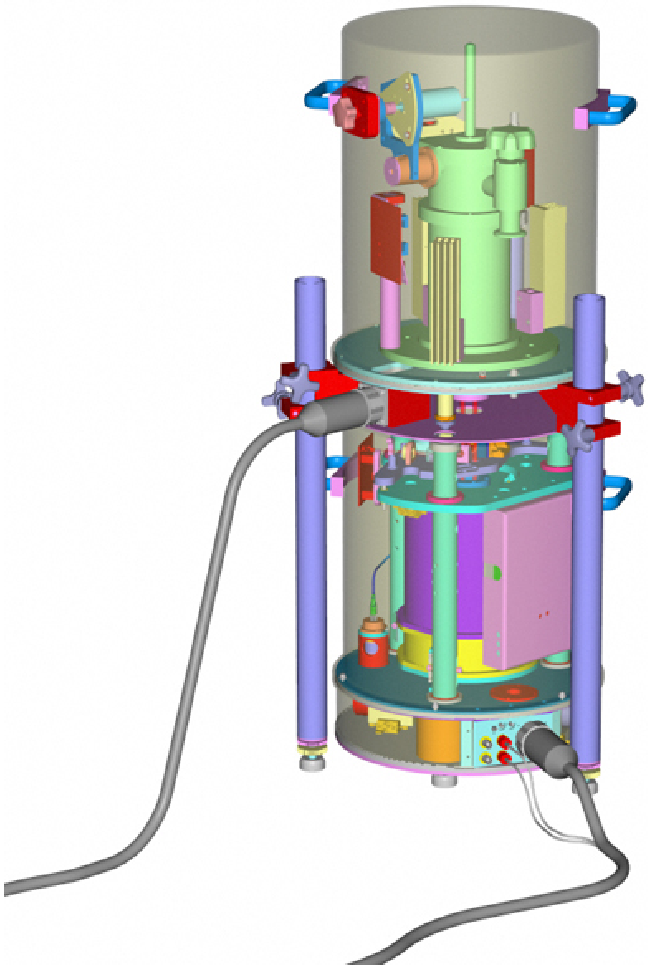
A10 Absolute Gravimeter



Micro-g LaCoste

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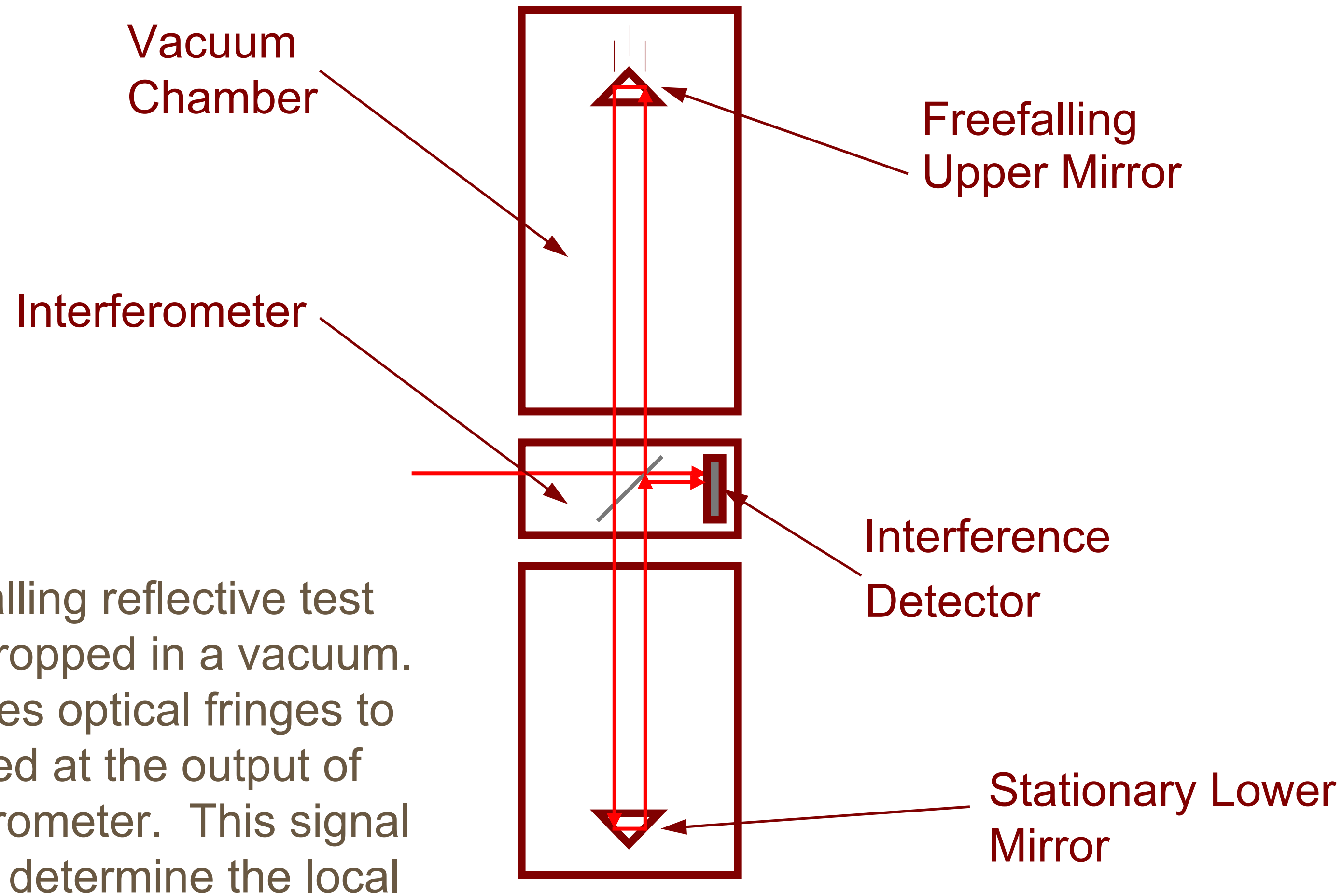
A10 Specifications

- Portable Laboratory Absolute Gravimeter
- Accuracy: 10 μGal (observed agreement between FGL instruments)
- Precision: at a quiet site, 10s drop interval, 50μGal/sqrt(Hz) [eg. About 1 μGal in 30 minutes]
- Operating dynamic range: World-Wide
- Operating temperature range: -15°C to 40°C

A10 Principle of Operation



A freely falling reflective test mass is dropped in a vacuum. This causes optical fringes to be detected at the output of an interferometer. This signal is used to determine the local gravitational acceleration.

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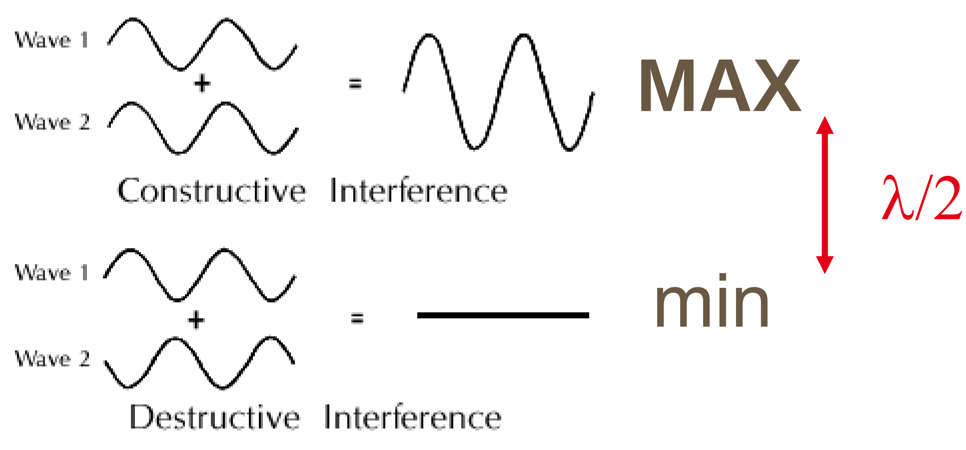
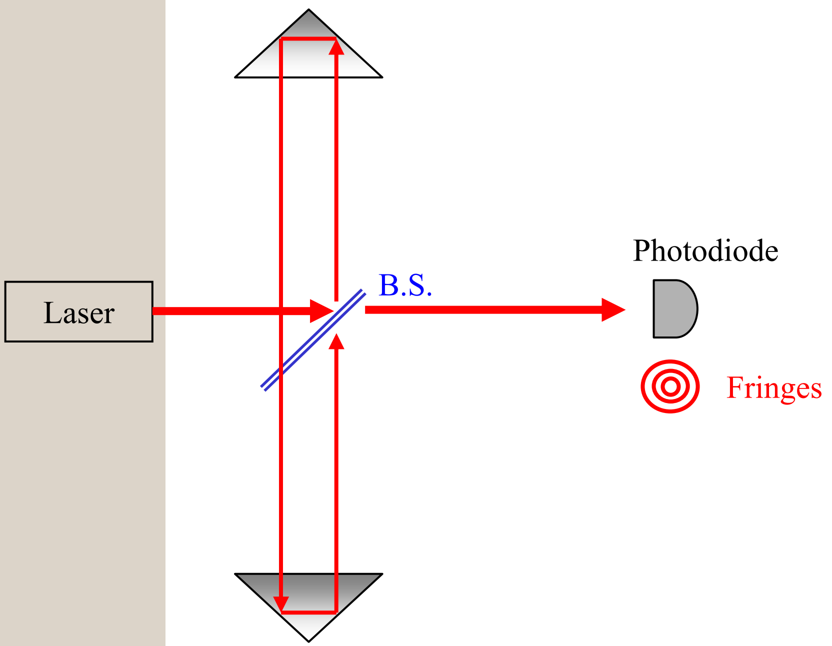
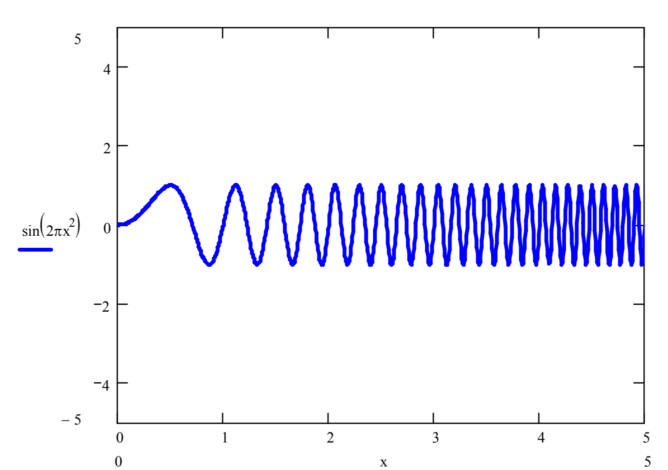
Interferometry





Michelson's interferometer

fringe signal sweeps in frequency as test mass falls under influence of gravity



time recorded (w.r.t. rubidium oscillator) at each minimum creating (t,d) pairs at every λ/2

g Determination

- Fringe = 1/2 x_i
- For each $\boldsymbol{x_i}$, a measured time $\boldsymbol{t_i}$,
- The following function is fitted to the data $\boldsymbol{x_i}$, $\boldsymbol{t_i}$:

$$\left.\begin{aligned} x_i &= x_0 + v_0\tilde{t}_i + \frac{g_0\tilde{t}_i^{\,2}}{2} + \frac{\gamma x_0\tilde{t}_i^{\,2}}{2} + \frac{1}{6}\gamma v_0\tilde{t}_i^{\,3} + \frac{1}{24}\gamma g_0\tilde{t}_i^{\,4} \\ \tilde{t} &= t_i - \frac{(x_i - x_0)}{c} \end{aligned}\right\} \quad x_i,\ t_i,\ \mathrm{i} = 1, \ldots, 700$$

- γ is the vertical gravity gradient (~3 µGal/cm),
- c the speed of light
- x_0 the initial position
- v_0 the initial velocity
- g_0 the initial acceleration

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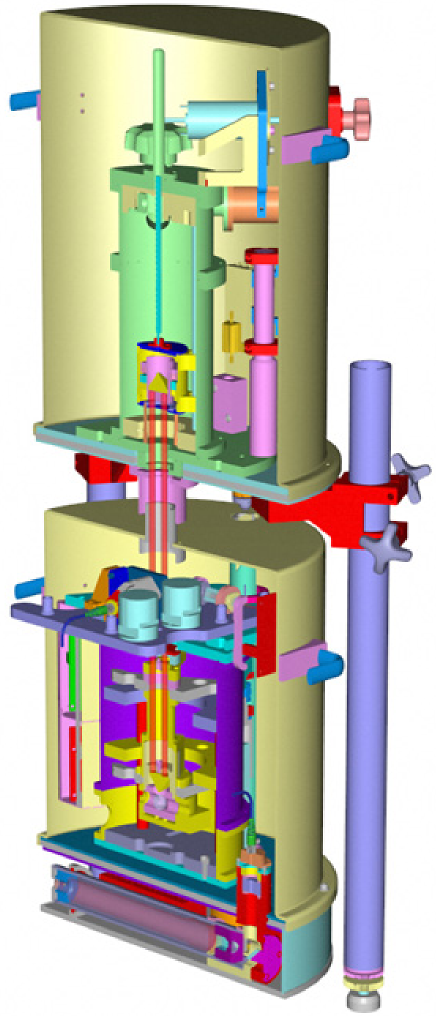
A10 Schematic



- Laser is frequency-stabilized He-Ne laser (red light @ 633 nm)
- Interferometer splits beam into **test** and **reference** beams
- The test beam bounces off falling corner cube then off stationary spring corner cube
- The reference beam travels straight through interferometer.
- Beams are recombined and interference signal (fringes) is used to track falling test mass
- The time intervals between the occurrence of each fringe are measured by a Rubidium oscillator

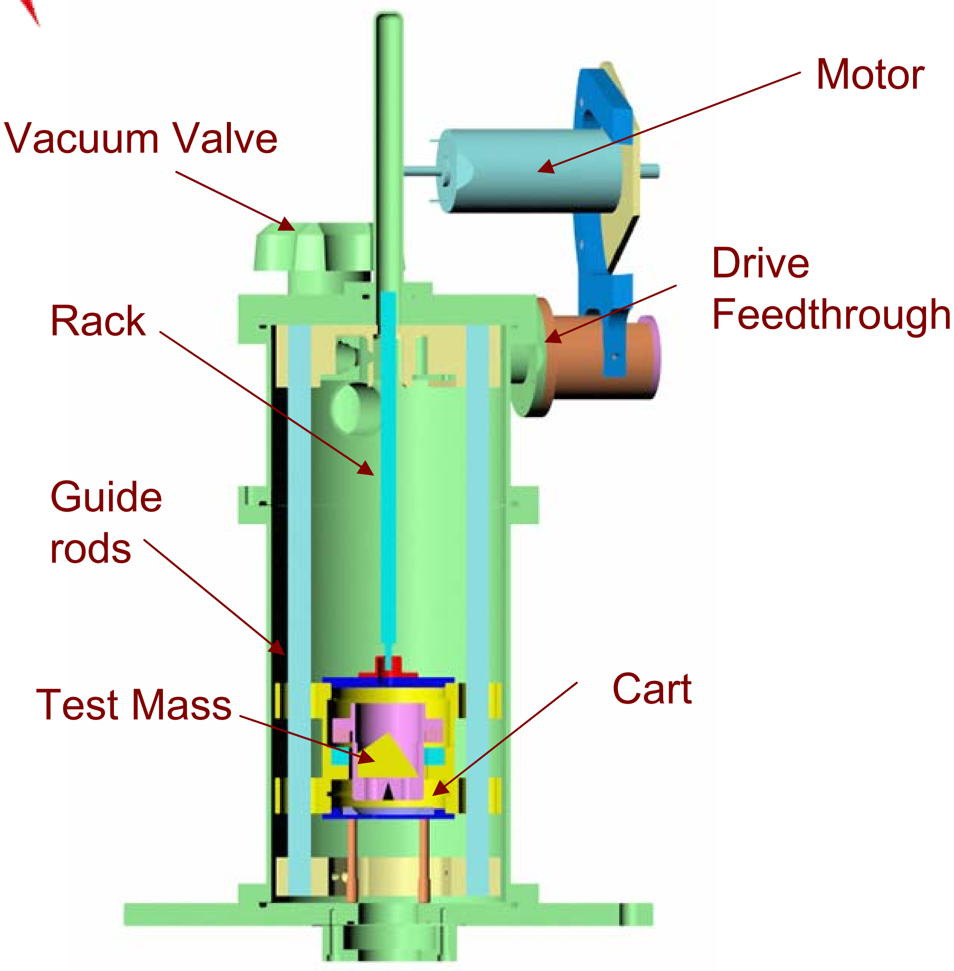
A10 Subsystems

- Upper Unit
  - Dropping Chamber
- Lower Unit (“IB”)
  - Superspring
  - Interferometer
  - Laser
- Electronics
- Software
  - Real-Time Data Acquisition
  - Post-Processing Data Analysis

A10 Dropping Chamber

- Drag Free Cart
- Mechanical Drive
- Vacuum system (Ion Pump 10^{-6} Torr)
- Test Object (ball&vee contacts)
  - Corner Cube
  - Lock Mechanism

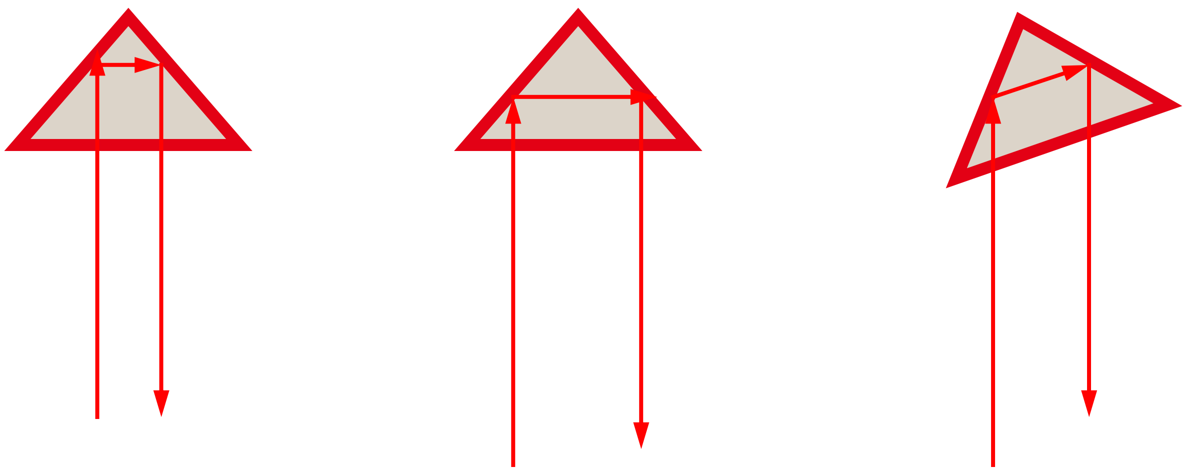
Drag-free Dropping Chamber



- Cart releases, follows, and gently catches the test mass
- Cart reduces drag due to residual gas molecules
- Shields the corner cube from external electrostatic forces
- Ion pump (not shown) maintains vacuum

Corner Cube Retroreflectors

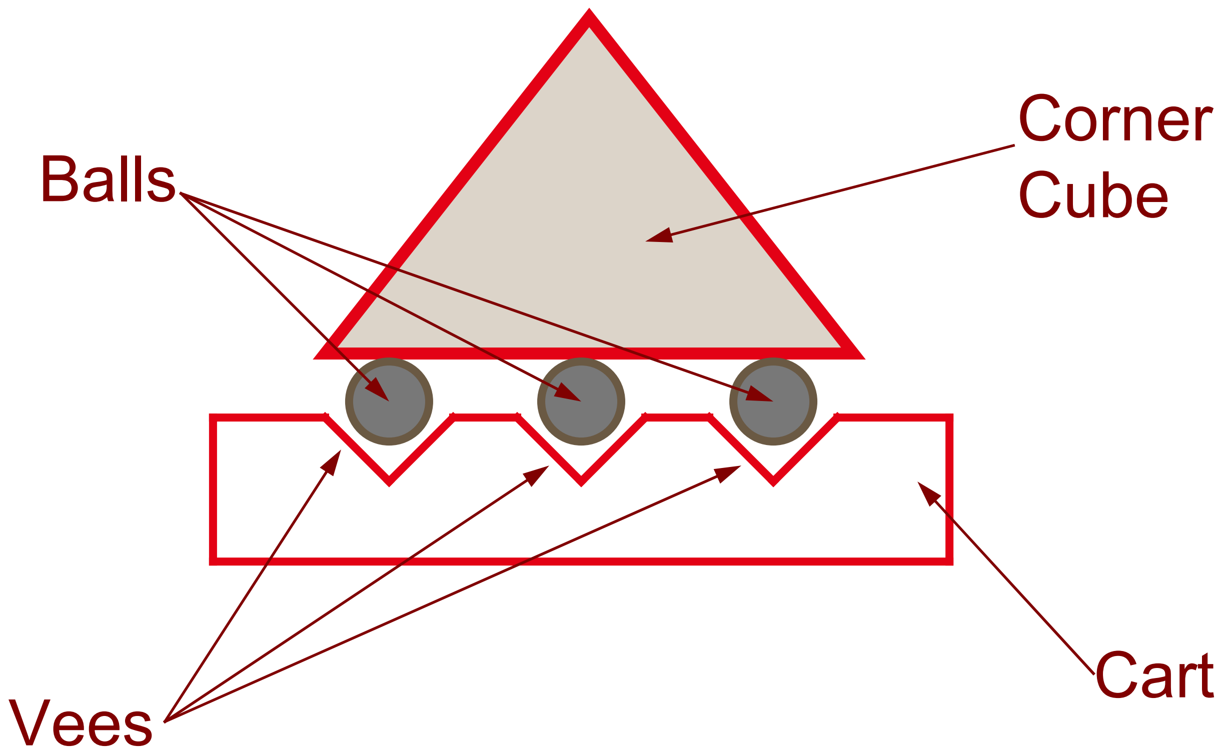
- Reflected ray parallel to input ray
- No phase change in wavefronts



- Insensitive to translation and rotation
- Used in both Dropping test mass and Stationary mass

Balls & Vees

- Re-orient dropper corner cube after each drop
- Tungsten parts (wear out). Typical lifetime ~500,000 drops (maximum ~1,00,000 drops, and depends on dropper tuning)
- Eventual replacement at Micro-g LaCoste factory



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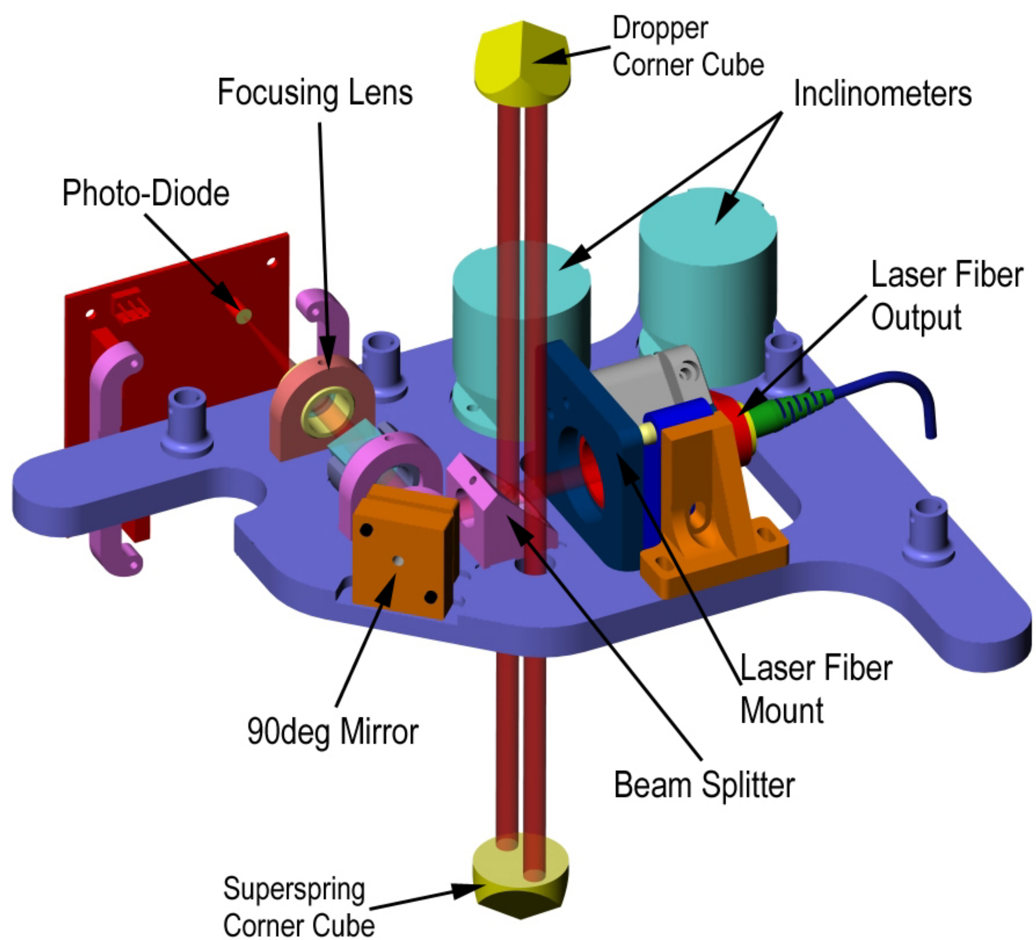
A10 Interferometer

- Self-overlapping
- One optical output
- Main signal interferometer (APD)
- Mirror to steer to Photodetector
- Two Electronic Output Signals
- Analog (Alignment)
- TTL (Timing)

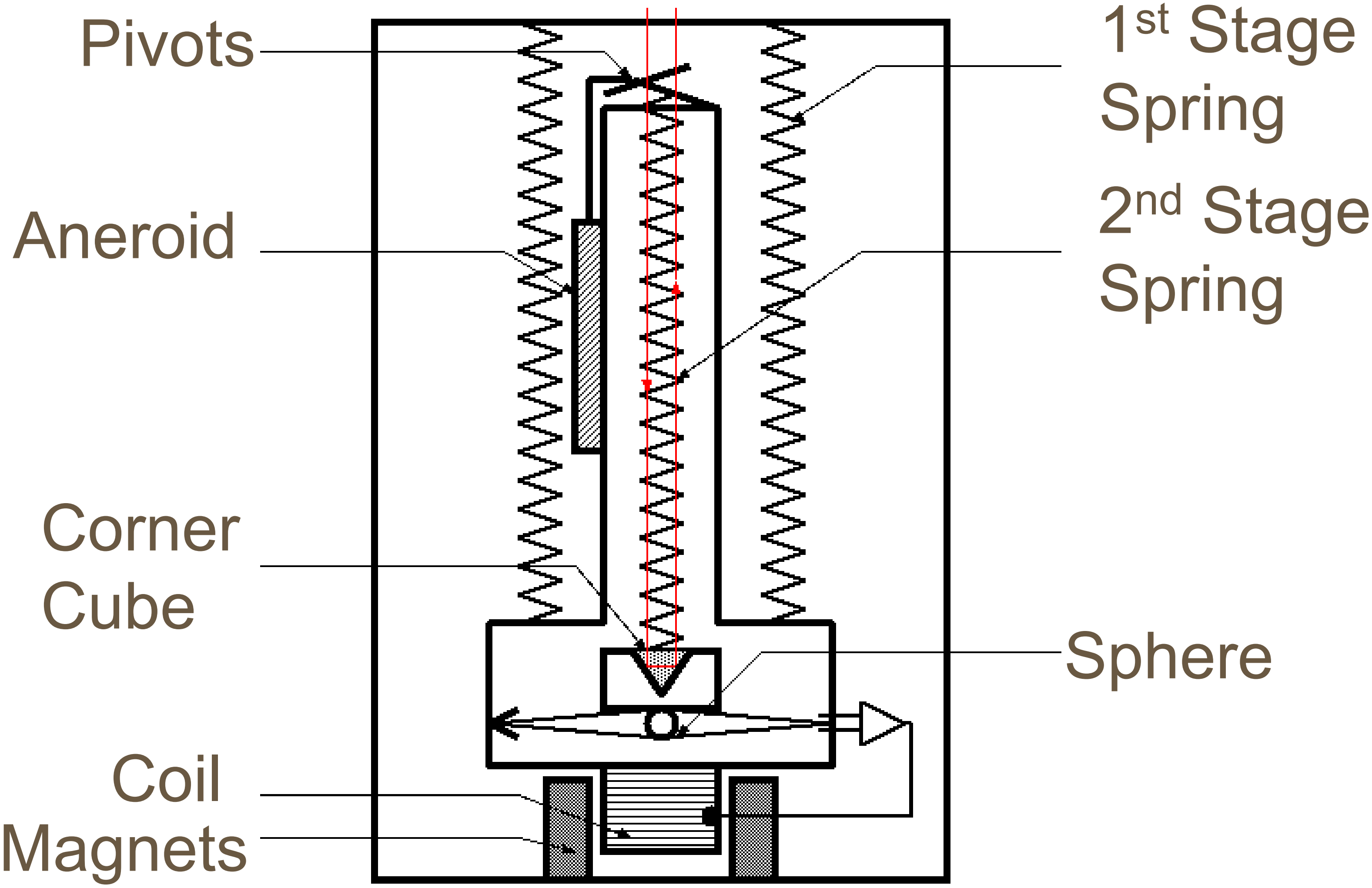


A10 Superspring

- 30s Period
- Two Stage nested spring system
- Sphere Detector
- Coil transducer
- Lock Mechanism
- Temperature compensation
- Spring height adjustment
- Bubble level adjustments

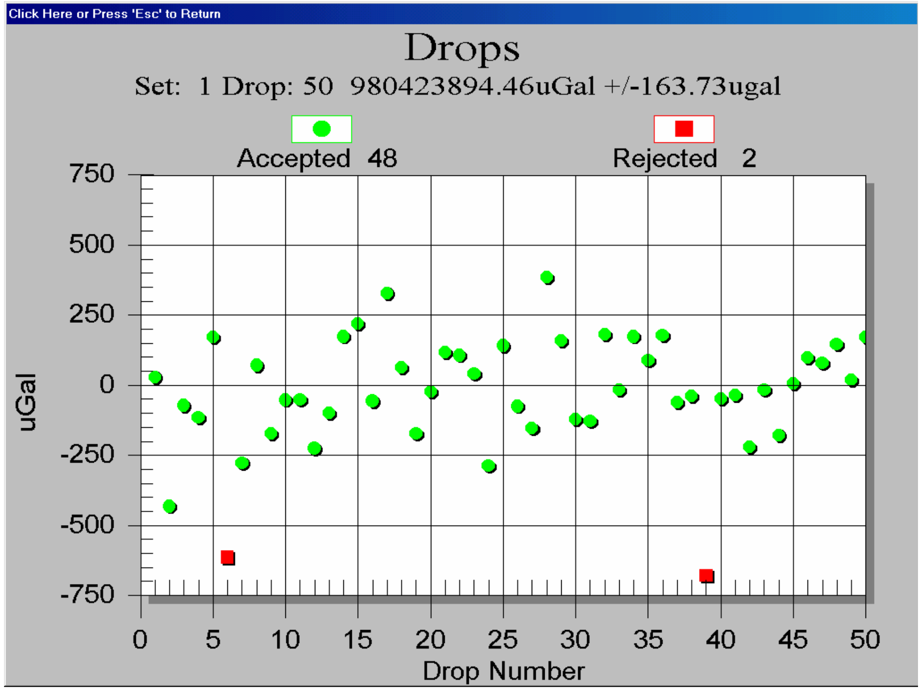
- Delta rods
- Zeroing the sphere position (S-shaped response)

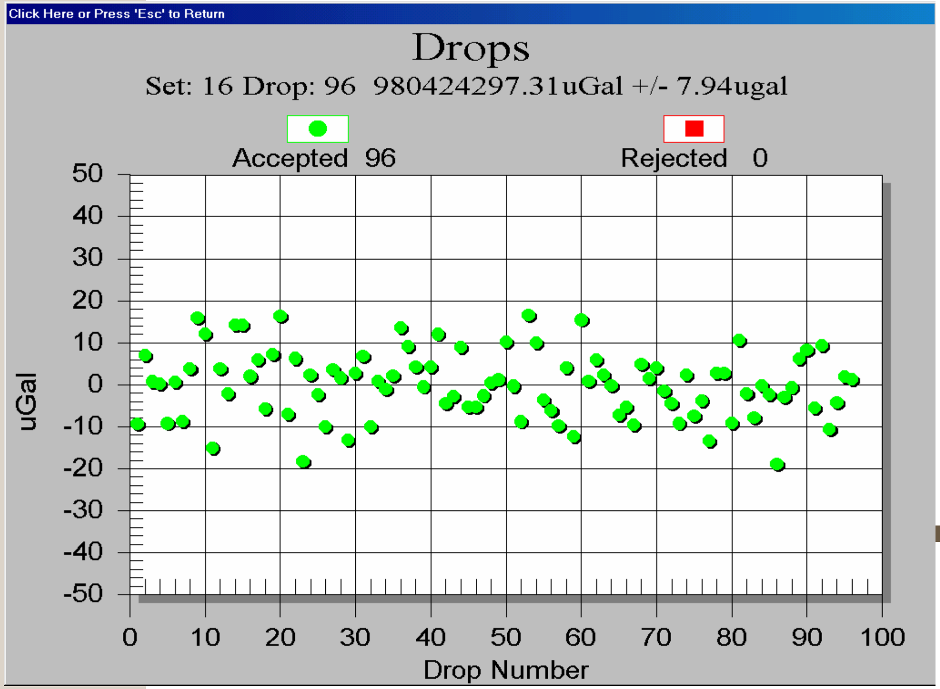
The Superspring (Cartoon)



Measurement Scatter

Without the superspring ...

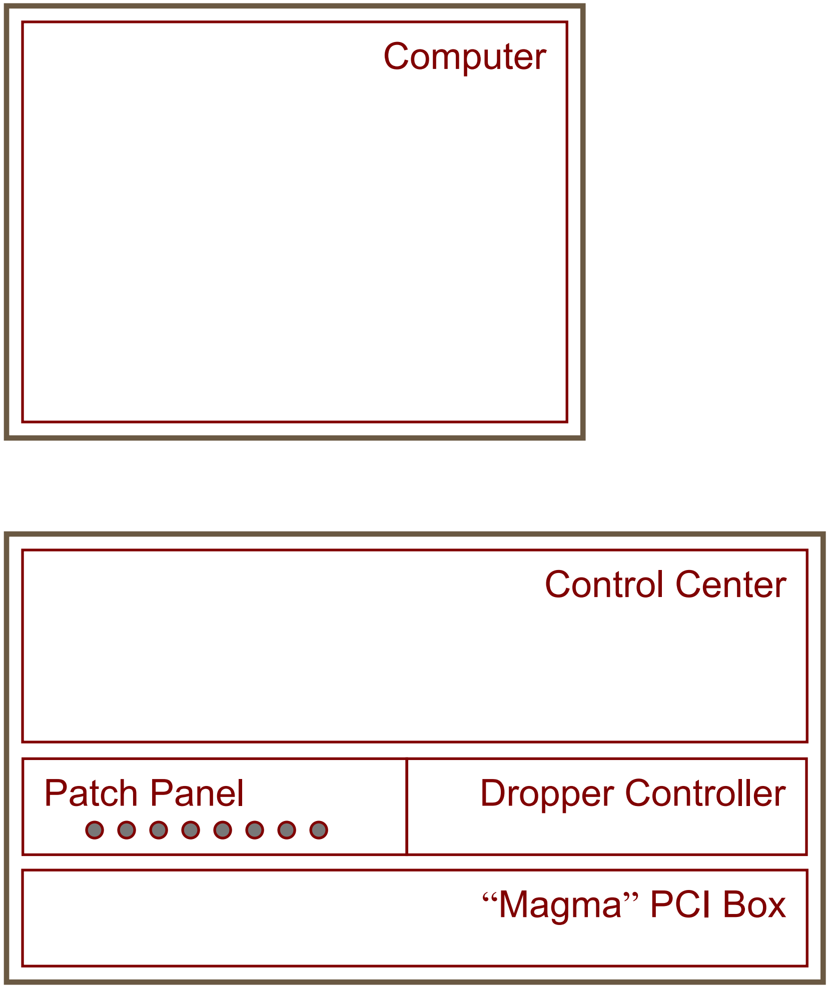




… and with the superspring

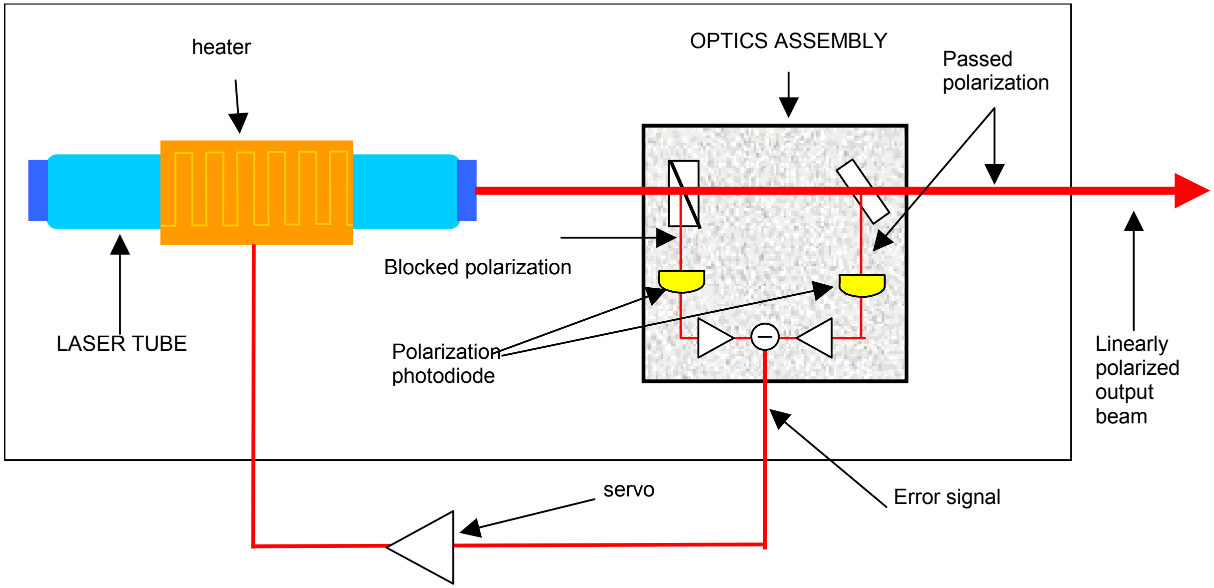
A10 Electronics

- Computer
  - Data acquisition & Reprocessing
- Main Power Supply
- Superspring Controller
- Dropping Chamber Controller
- Ion pump power supply
- Laser Controller
- Patch Panel
  - Analog & Digital IO



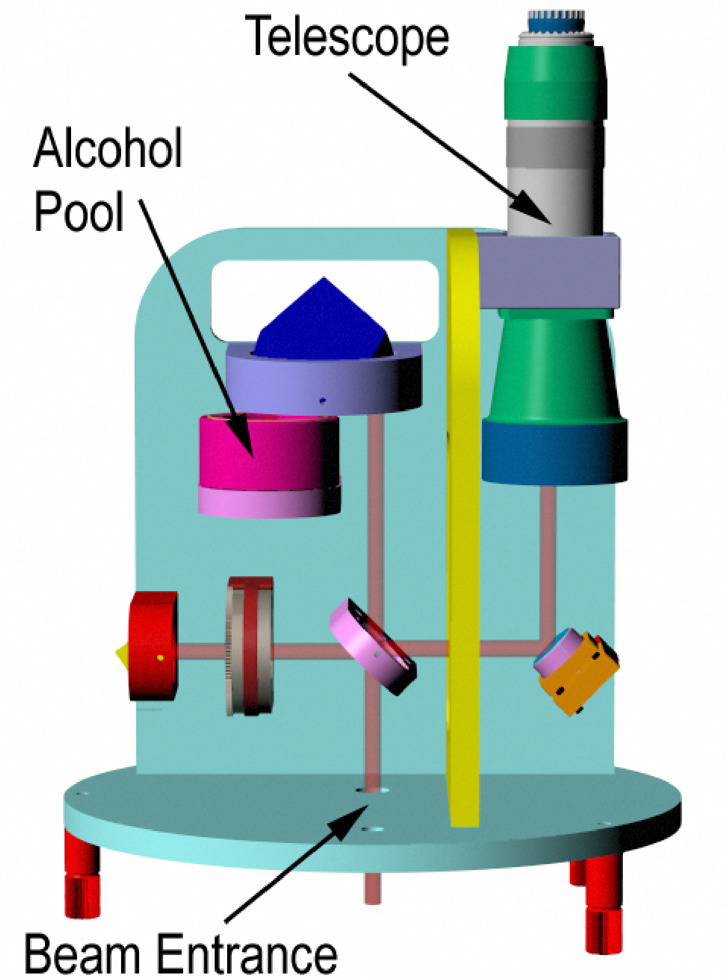
ML-1 Polarization Stabilized Laser

- Calibrated to Primary Standard (WEO Iodine Laser – recommended once per year)
- Accuracy at ~2 parts in 10^9
- Two modes, automatically switched between sets. Average should be stable with temperature
- Fiber launching system:
  - Faraday Isolator
  - 5-axis stage
  - Single mode fiber
  - Output collimation:
    - (6mm)



Beam (Verticality) Checker

- Deviations from verticality result in gravity values that are too low. Error ~ θ^2
- Though the meter is self-aligning, verticality can be verified by placing the "beam checker" on top of the IB.
- Alcohol pool provides level standard
- Adjustments, if necessary, are made using the "pots" on the IB cable connection plate



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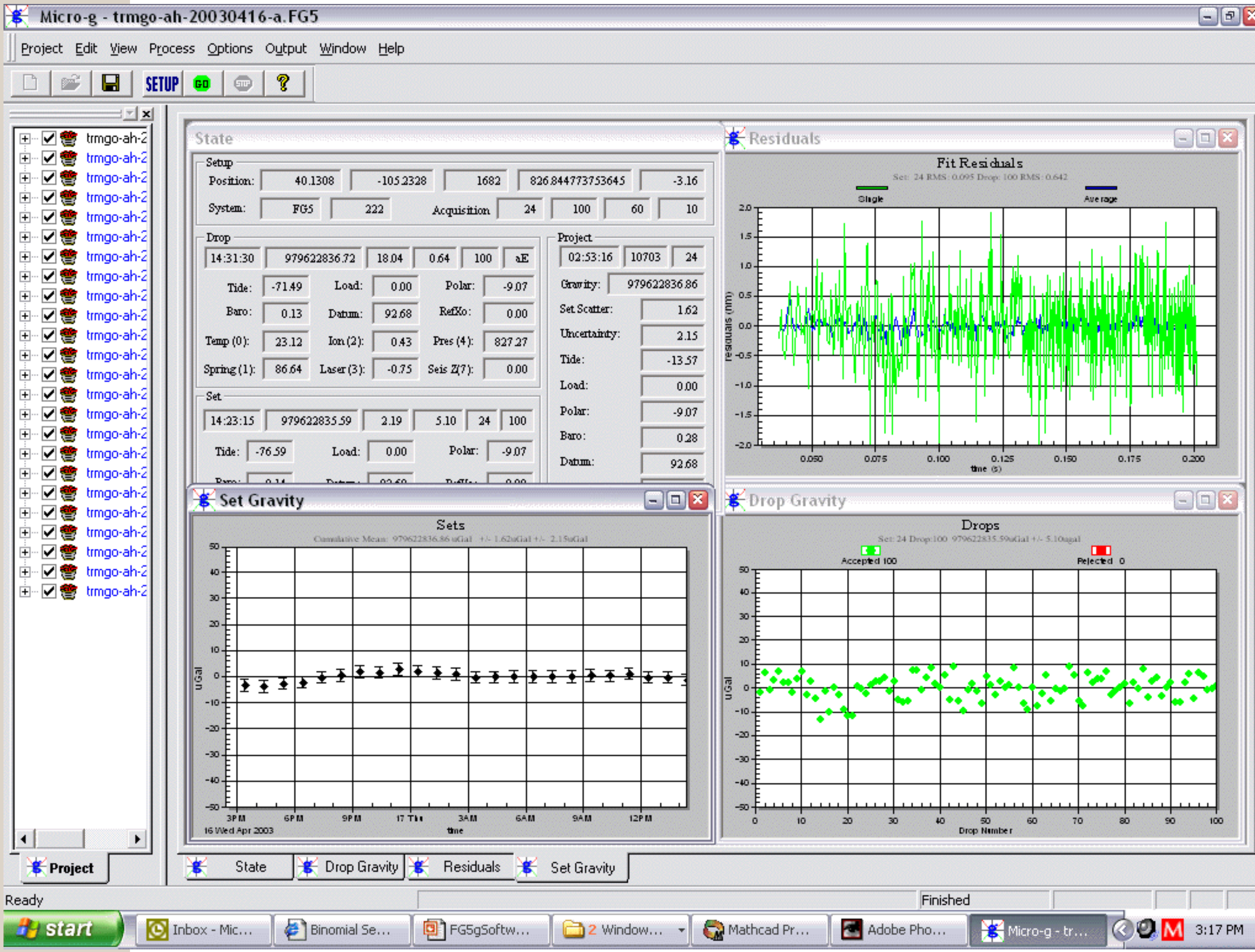
Regular Maintenance

- Regular maintenance of the system at Micro-g LaCoste is necessary
- Typically after ~500,000 drops (maximum ~1,00,000 drops)
- Dropper rack & pinion wear
- Optics Cleaning
- Ferrofluidic feedthrough replacement
- Ion pump degradation (plating)
- Ball & Vee wear
- Laser tube degradation

g Gravity Acquisition and Processing Software



- Windows Based
- Graphics package
- Gravity corrections
- Earth Tide Models
- Ocean Load Correction
- Statistical analysis
- Real time data acquisition
- Post processing

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g Software control

- Site Specification
- Instrument Parameters
- Data Acquisition Parameters
- Gravity Corrections
- Graphics
- Reports

g Input Parameters

- Site Specification
  - Latitude
  - Longitude
  - Elevation (std pressure)
  - Gradient (-3.1 μGal/cm)
  - Polar Motion
- Data Acquisition Parameters
  - Number of drops/set
  - Number of sets
  - Interval between drops (normally 1s)
  - Start time of data acquisition
  - Projects (sets of sets)

Gravity Corrections & Error Sources

- Gravity Corrections
  - Earth Tides
  - Ocean Loading
  - Barometer
  - Polar motion
  - Gradient
  - Speed of Light
- Error Sources
  - Verticality: 9 arcsec = 1μGal
  - "1 spot" = 4μGal
  - Water Table: 2.5 cm = 1μGal

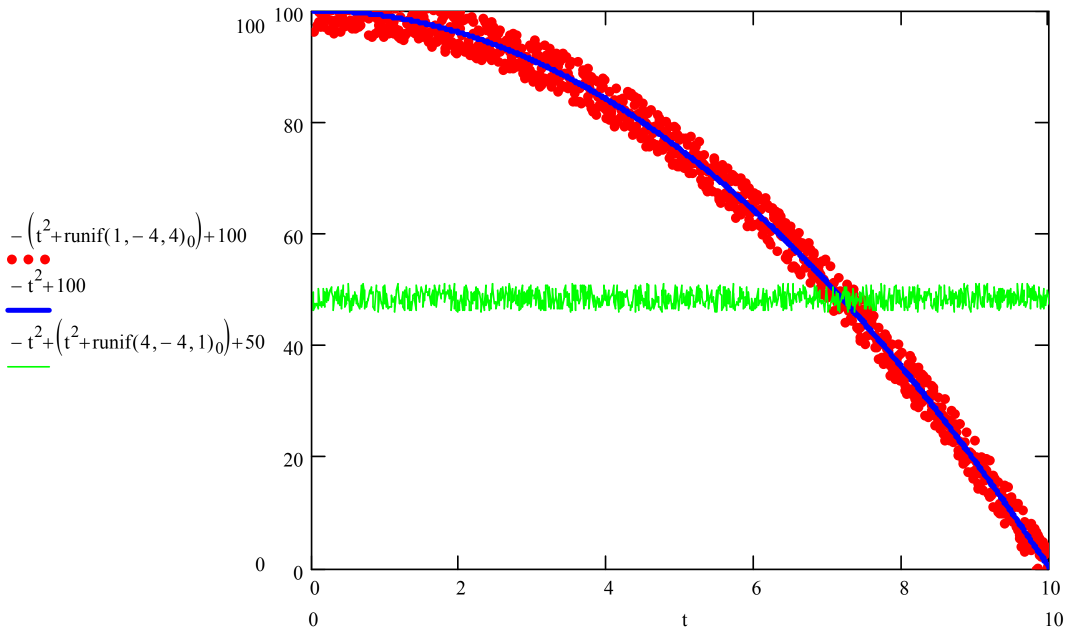
- T.M. Niebauer *et al*, Metrologia, 1995, **32**, 159-180

Prescaling & g Fit Example

Prescale*Multiplexor = 1000   Total #Fringes = 250

recorded fringe #	actual # of fringes	time (s) T	distance (mm) X
1	1	0.0003	0.0003
2	1001	0.008	0.300
3	2001	0.0114	0.600
.	.	.	.
.	.	.	.
250	250001	0.127	79.0

Residuals



A Residual is the distance (nm) between the measured object location and the least squares fit estimate at a given time.

Measurements
Best Fit
Residuals

Note: vertical scale exaggerated, normal residuals are approximately 1nm.

Simple Statistics: "How much data should I take?"

- First, some definitions:
  - σ = drop scatter (standard deviation of measurements)
  - δ_{stat} = statistical uncertainty
  - δ_{sys} = systematic uncertainty ("built in" system uncertainty and model uncertainties)
  - δ_{total} = sum, in quadrature, of statistical and systematic uncertainties

$$\delta_{stat} = \sigma / \sqrt{N_{drops}}$$

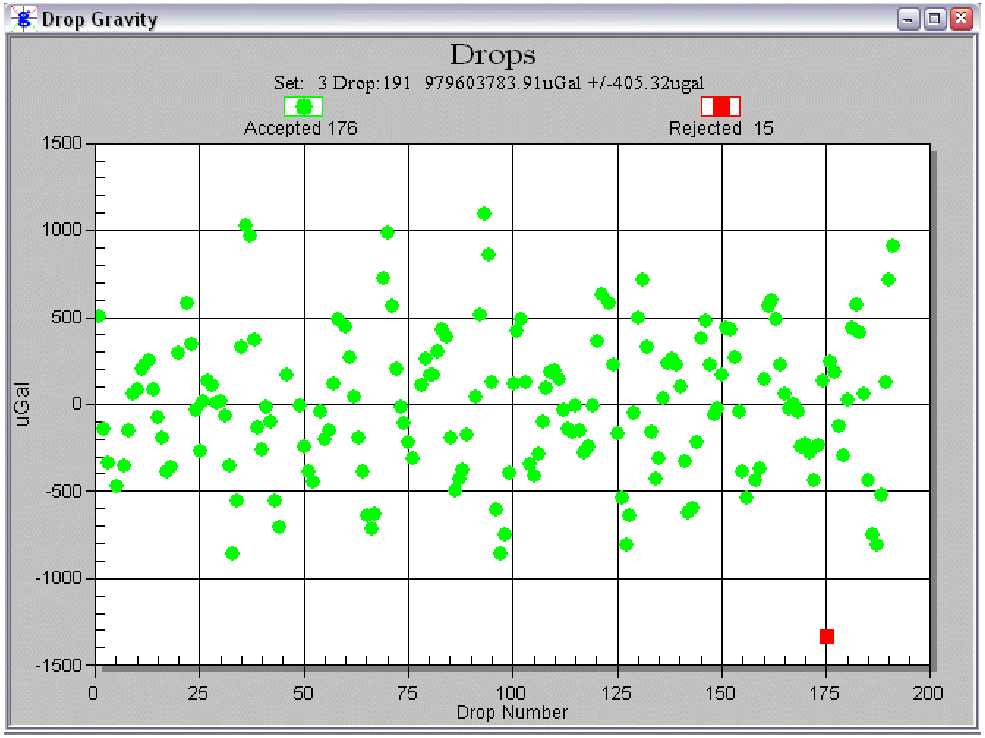
$$\delta_{total} = \sqrt{\delta_{sys}^2 + \delta_{stat}^2}$$

- Measure drop scatter, σ
- Pick your desired statistical uncertainty, δ_{stat}
- This determines N_{drops}
- Spread this N_{drops} over a convenient number of sets.

Remember the balls & vees: only run as long as you need to!

Simple Statistics Cont…

A10: ~10μGals Systematic Uncertainty



Example:

- Drop scatter = 400μGals
- 10μGals statistical uncertainty => ~1600 drops

- Lifetime ~1,000,000 drops => 600 site occupations

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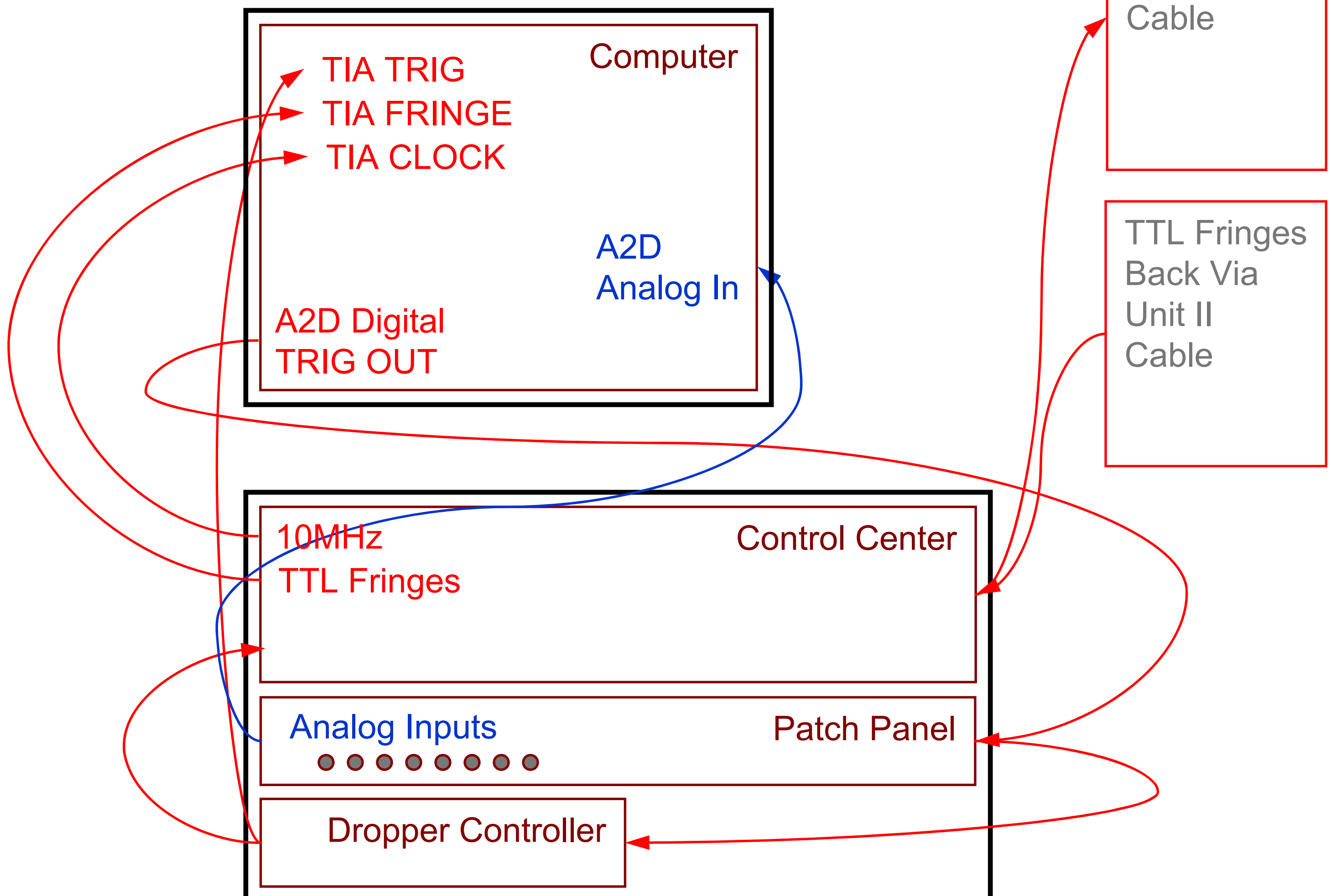
Electronics Flowchart



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