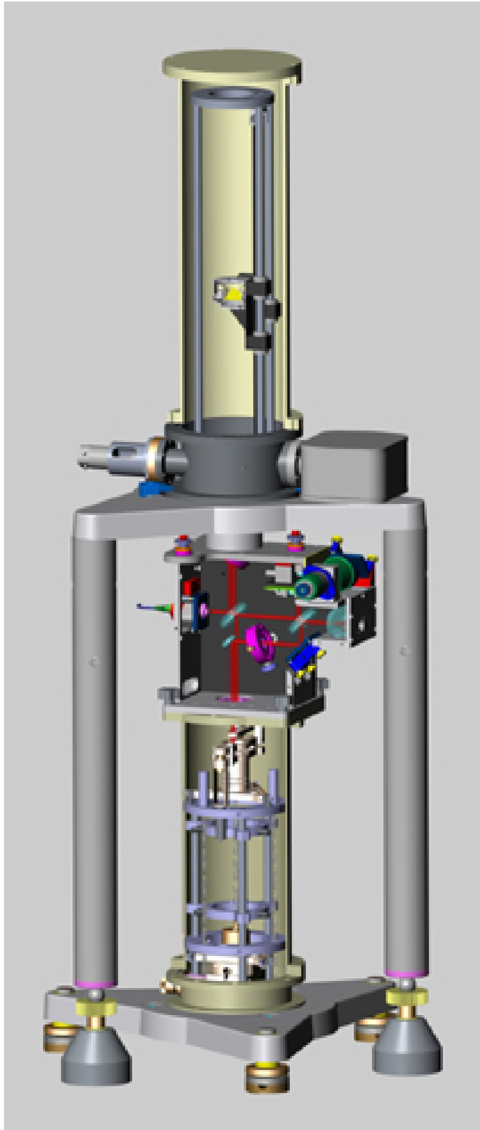


FG5 Absolute Gravimeter

Micro-g LaCoste

Derek van Westrum, Ph.D.

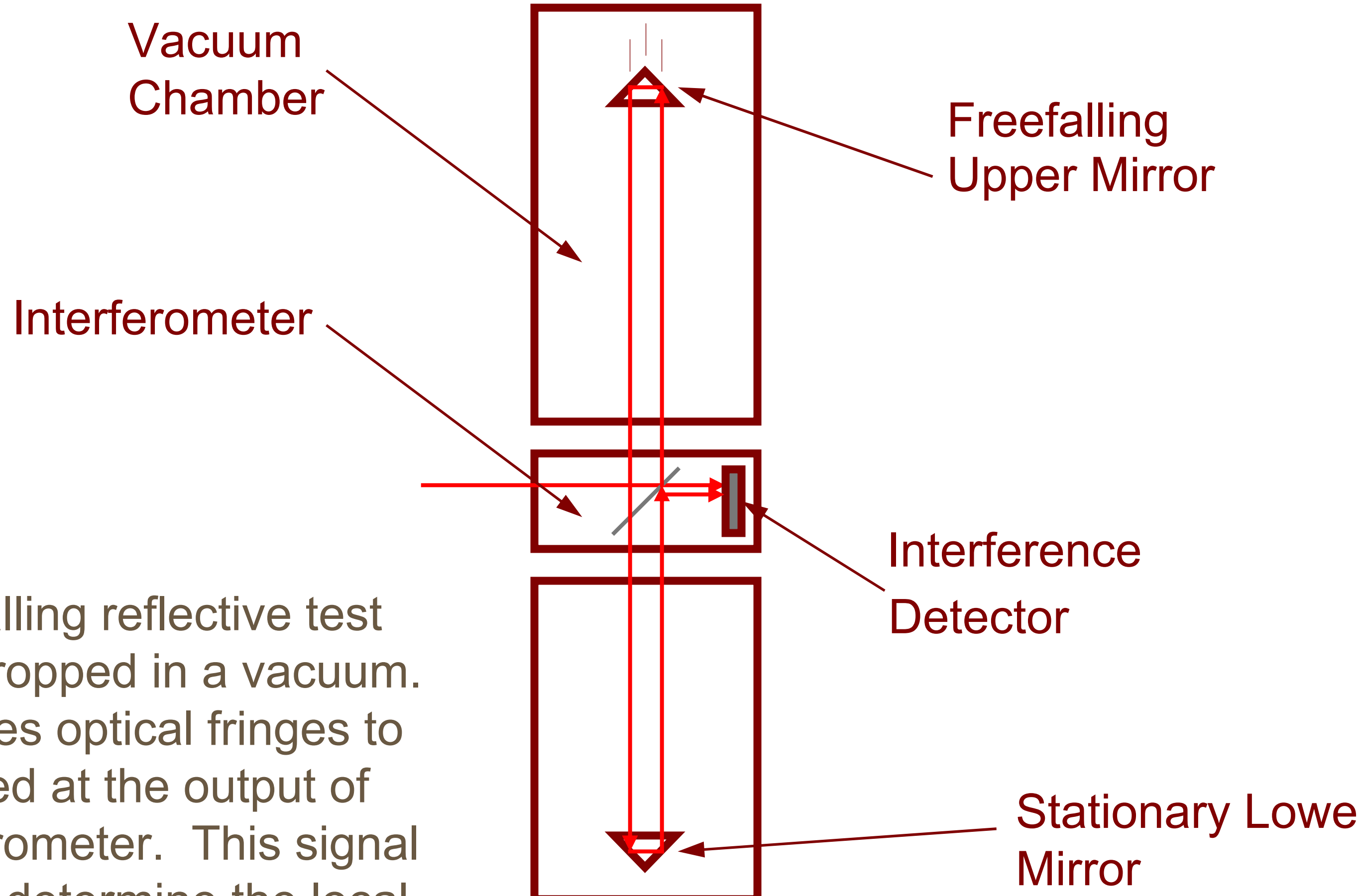
www.microglacoste.com

derek@microglacoste.com

FG5 Specifications

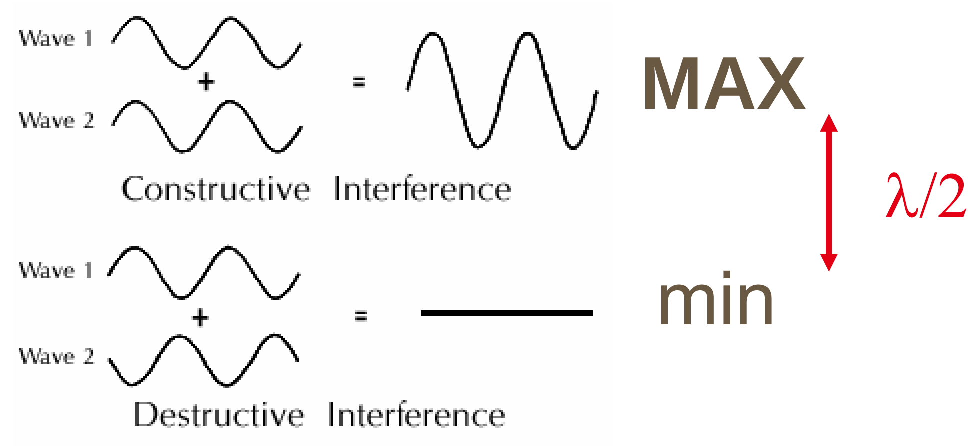
- Accuracy: 2 μGal (observed agreement between FG5 instruments)
- Precision: at a quiet site, 10s drop interval, 15μGal/sqrt(Hz) [eg. About 1 μGal in 3.75 minutes or 0.1microGal in 6.25 hours]
- Operating dynamic range: World-Wide
- Operating temperature range: 15°C to 30°C

FG-5 Principle of Operation

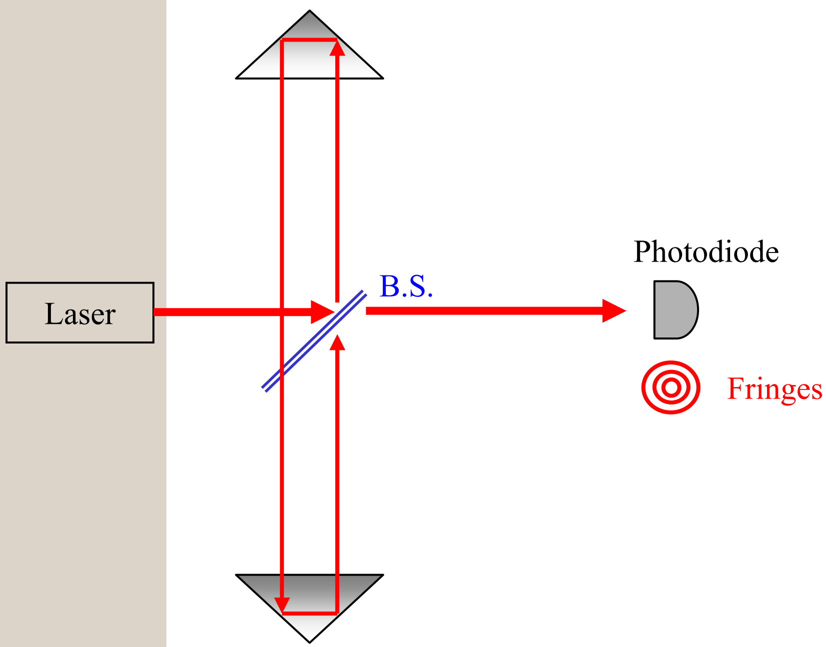


A freely falling reflective test mass is dropped in a vacuum. This causes optical fringes to be detected at the output of an interferometer. This signal is used to determine the local gravitational acceleration.

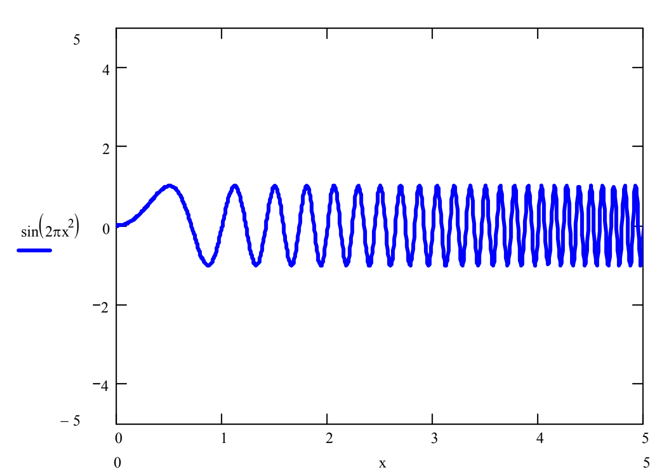
Interferometry



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



Michelson's interferometer



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

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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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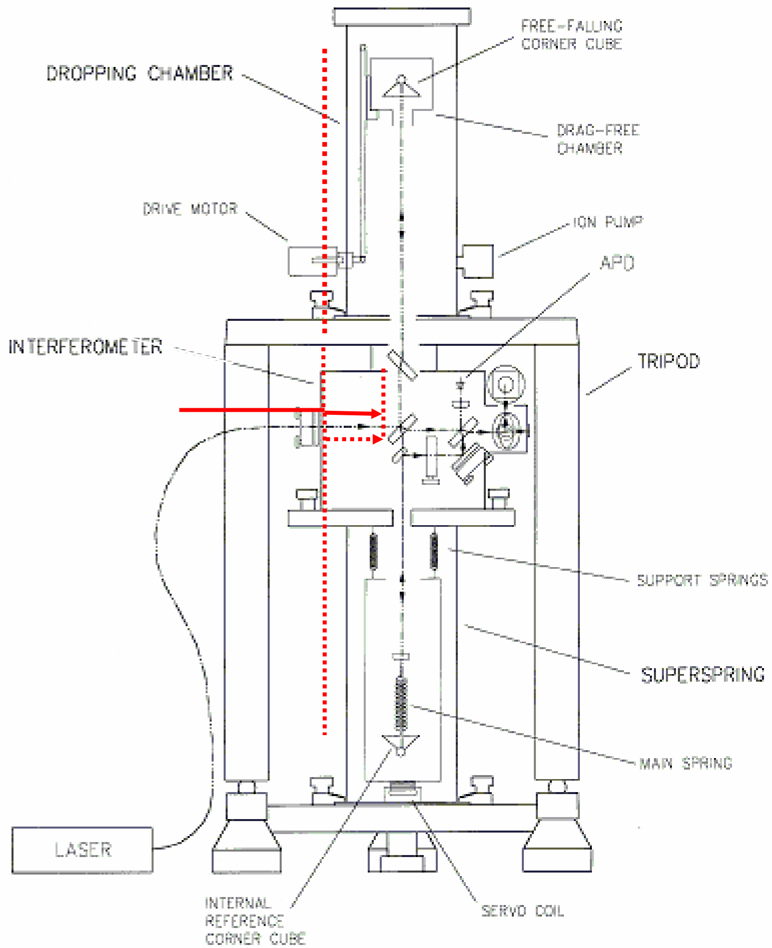
FG5 Schematic



- 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

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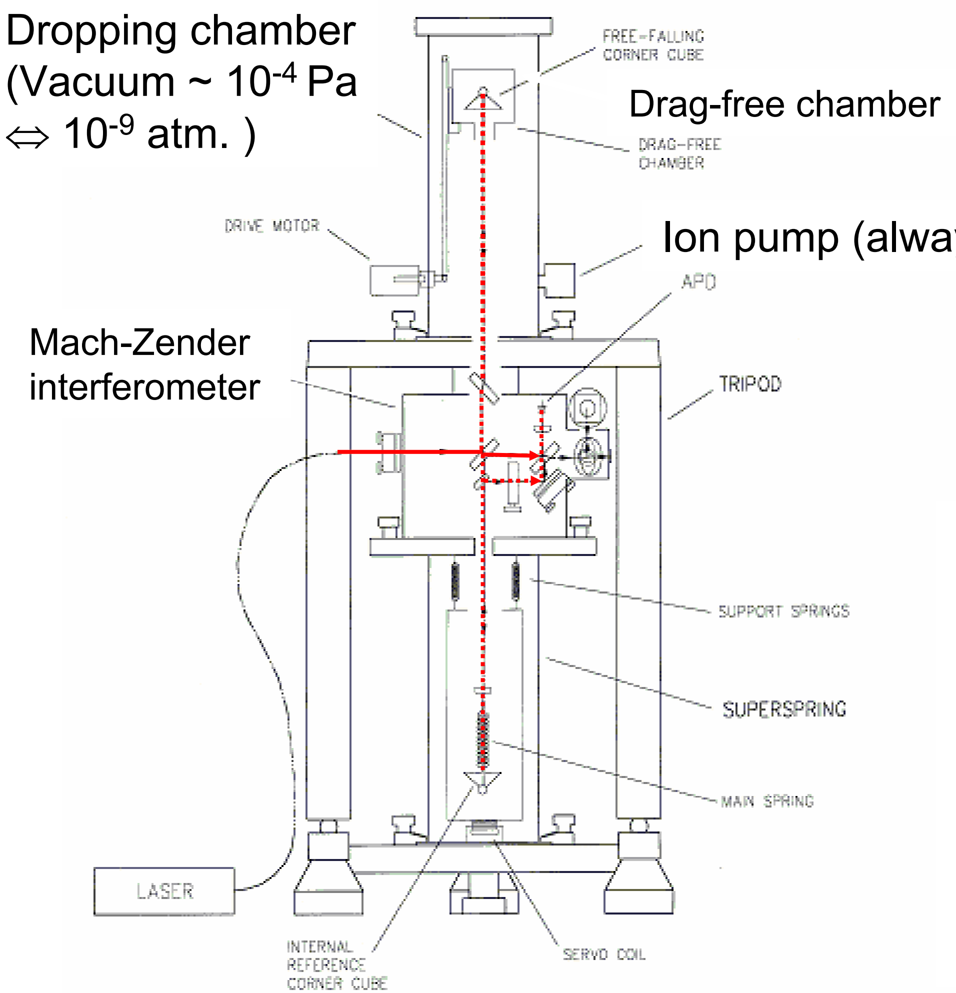
FG5 Subsystems

- Dropping Chamber
- Superspring
- Interferometer
- Laser
- Electronics
- Software
  - Real-Time Data Acquisition
  - Post-Processing Data Analysis

FG5 Dropping Chamber

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

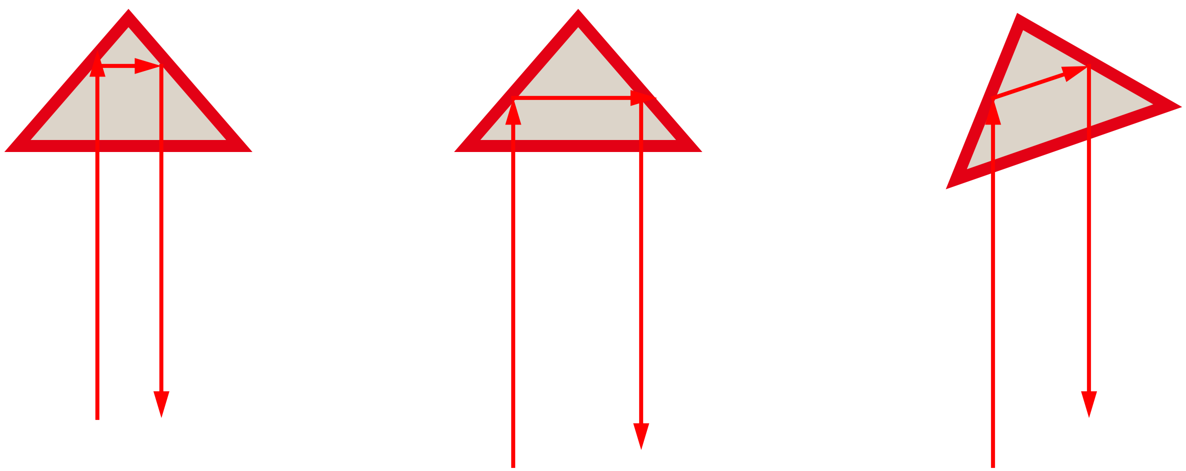
Drag-free Dropping Chamber



- Reduces drag due to residual gas molecules
- Follows the dropped corner cube, gently arrest and lift it
- Shields the corner cube from external electrostatic forces

Corner Cube Retroreflectors

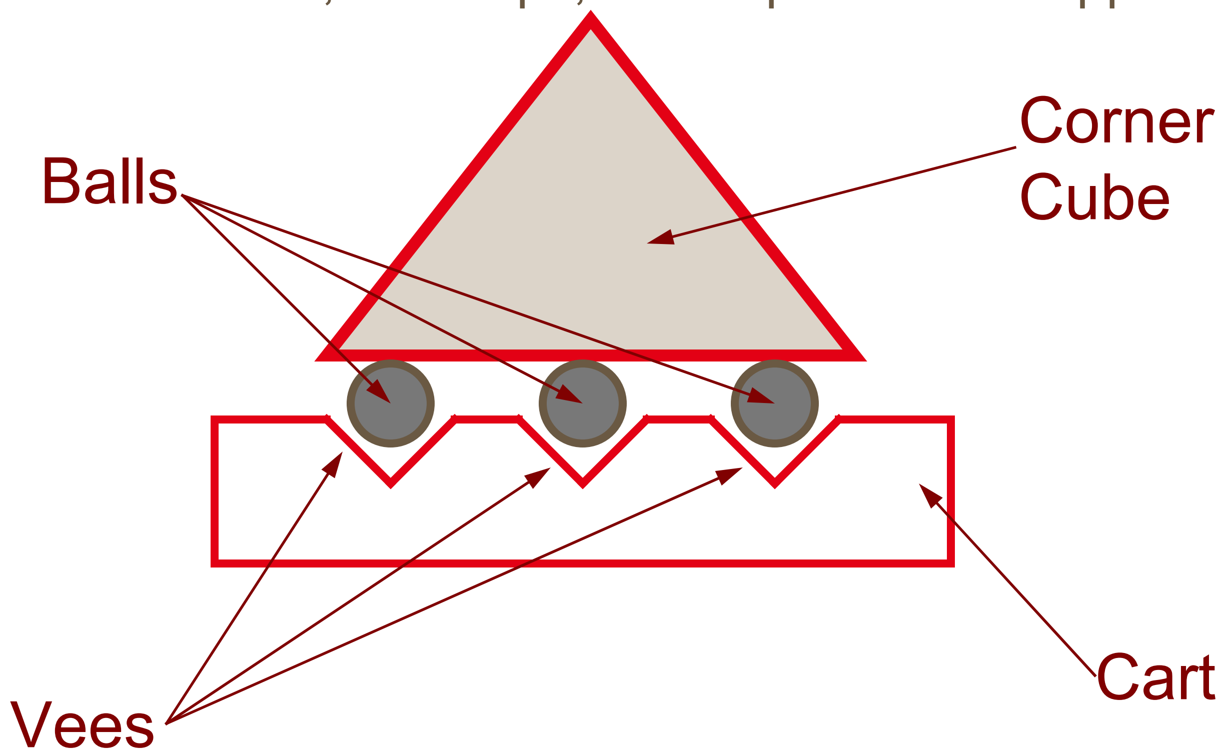
- Reflected ray parallel to input ray
- No phase change in wavefronts



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

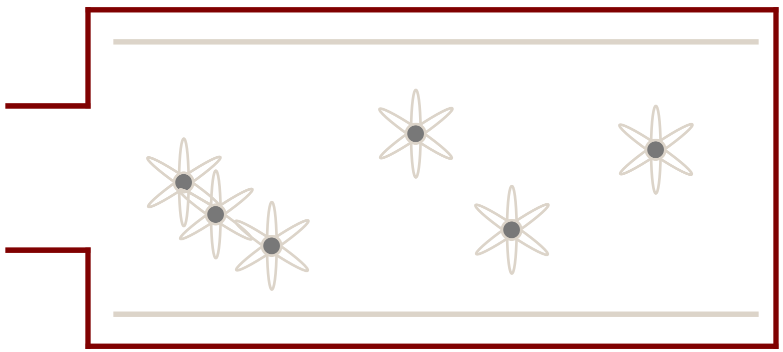
Balls & Vees

- Re-orient dropper corner cube after each drop
- Tungsten parts (wear out). Typical lifetime ~250,000 drops (maximum ~500,000 drops, and depends on dropper tuning)



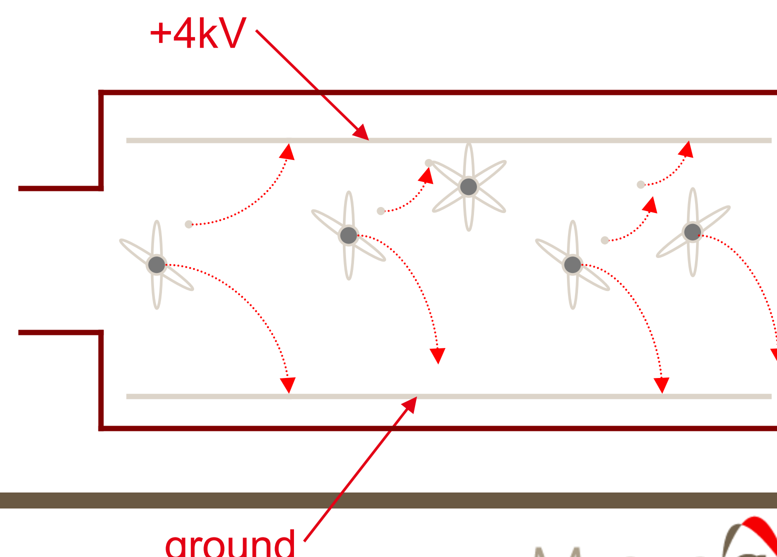
Ion Pump

- Vacuum is maintained by an ion pump
- No moving parts, high voltage used to ionize molecules and "plate" them out



- Before pumping process begins, neutral atoms and molecules float in ion pump area

- When process starts, electrons are attracted to the positive voltage, and ions to the ground.
- Liberated electrons ionize other molecules, forming a "pumping" action



Ion Pump (cont.)

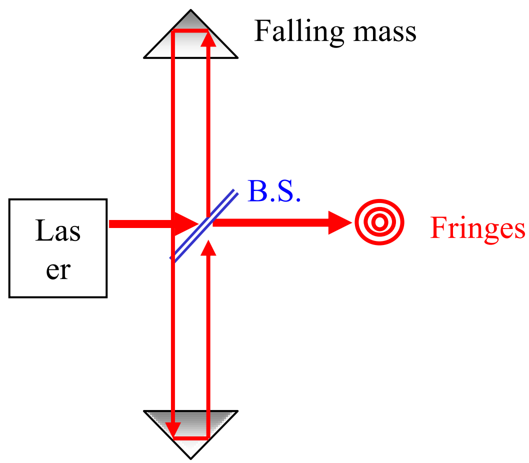
- Electrical current drawn by ion pump power supply is proportional to # of molecules ionized
- Therefore electrical current is proportional to pressure

- Vacuum level must be very good (< 10^{-5} Torr) before ion pump can be operated
- Vacuum started with mechanical turbo pump

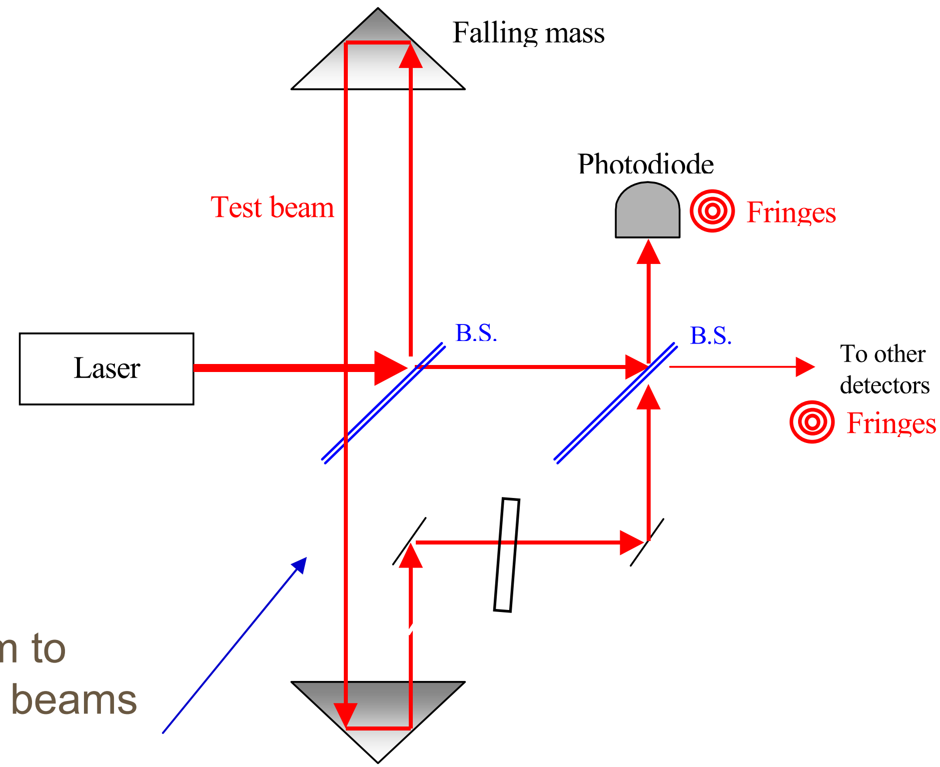
- Limited life time (~5 years)

Mach-Zender Interferometer

Michelson's Interferometer



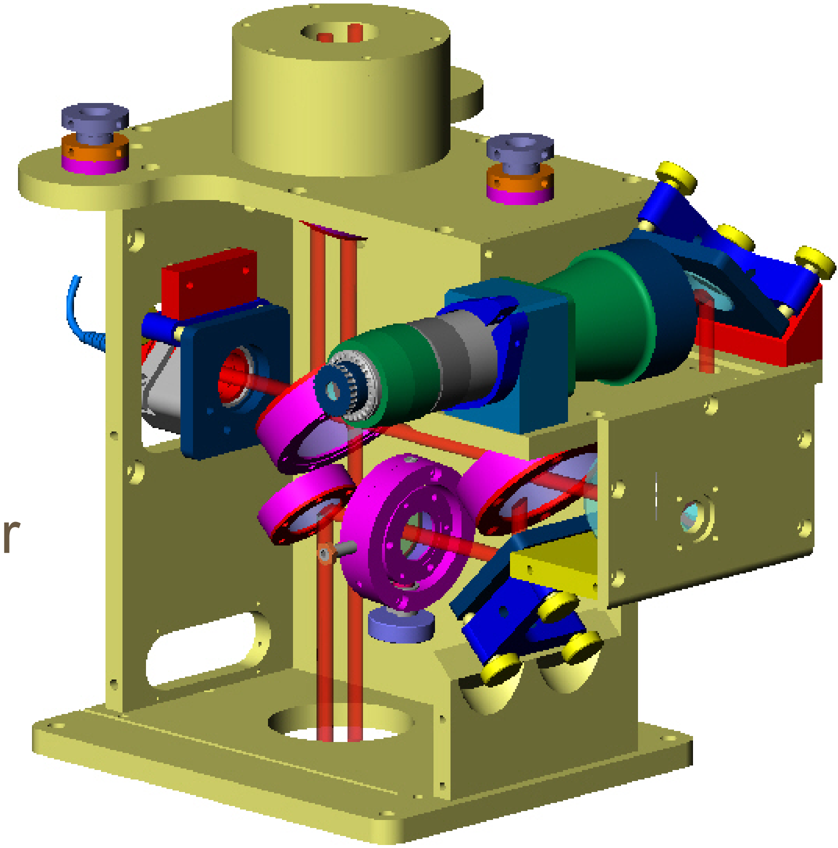
Mach-Zender's interferometer: 2 beam splitters



Allows complete freedom to make the two interfering beams collinear (parallel and overlapped) for optimal fringes contrast

FG5 Interferometer

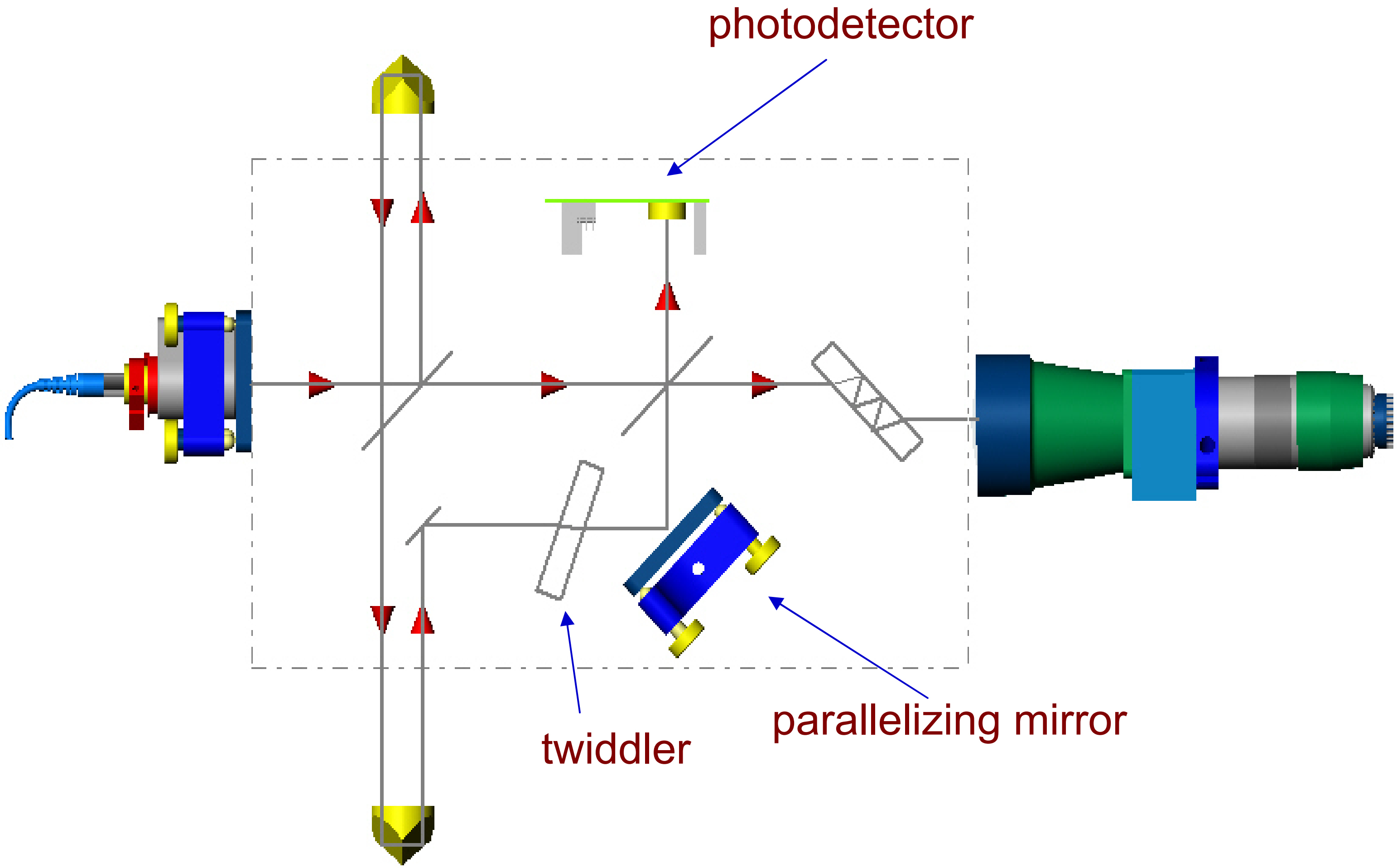
- Mach-Zender type
- Insensitive to rotations and translations
- Three optical outputs
  - Main signal interferometer (APD)
  - Telescope (verticality and/or beam alignment)
  - Viewing port
- Two Electronic Signals
  - Analog (Alignment)
  - TTL (Timing)



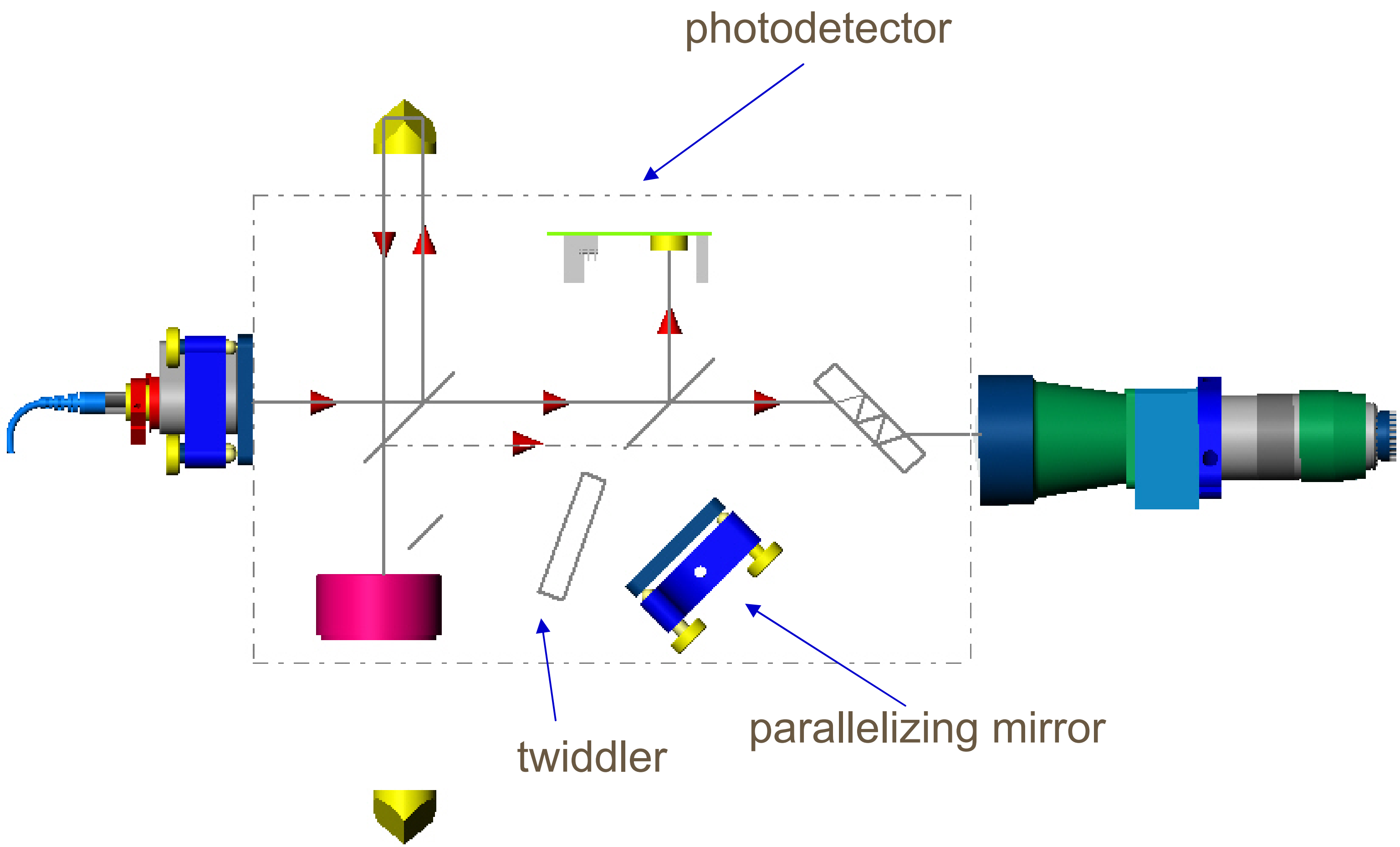
FG5 Interferometer Adjustments

- Input beam fiber adjustment (test beam verticality)
- Twiddler (beams coincident)
- Final test beam mirror (beams parallel)
- Alignment of beams onto photodetector

Beam Path



Beam Verticality



Note that the twiddler and the parallelizing mirror do nothing!

FG5 Superspring

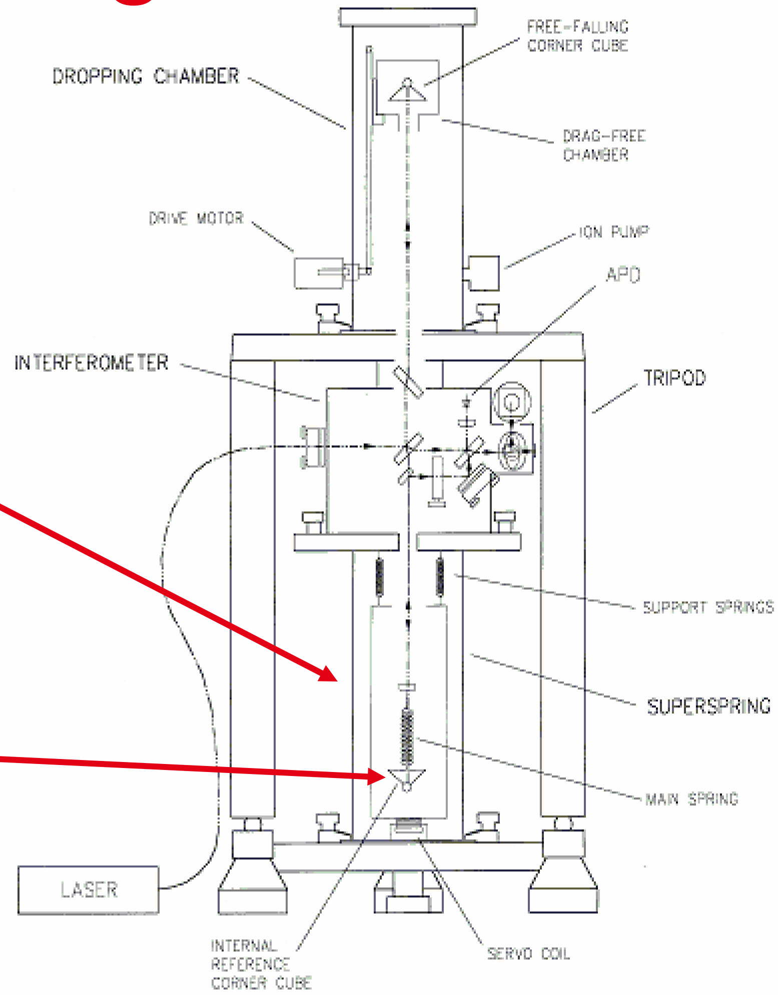
- 60s Period
- Two Stage nested spring system
- Sphere Detector
- Coil transducer
- Lock Mechanism
- Temperature compensation
- Spring height adjustment
- Bubble level adjustments

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

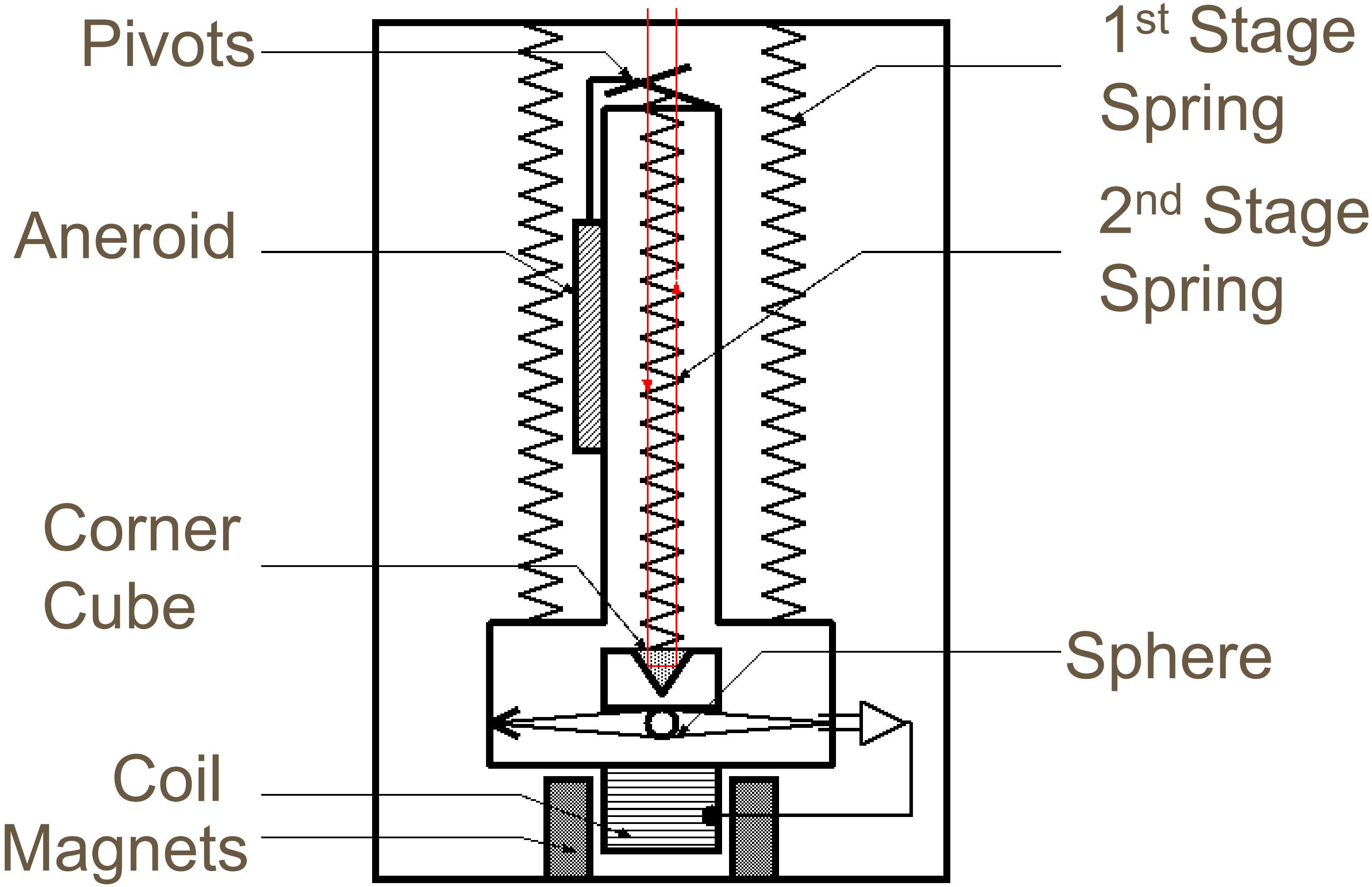
The Superspring

The superspring: long period isolation spring that provides the inertial reference frame

Inertial reference corner cube

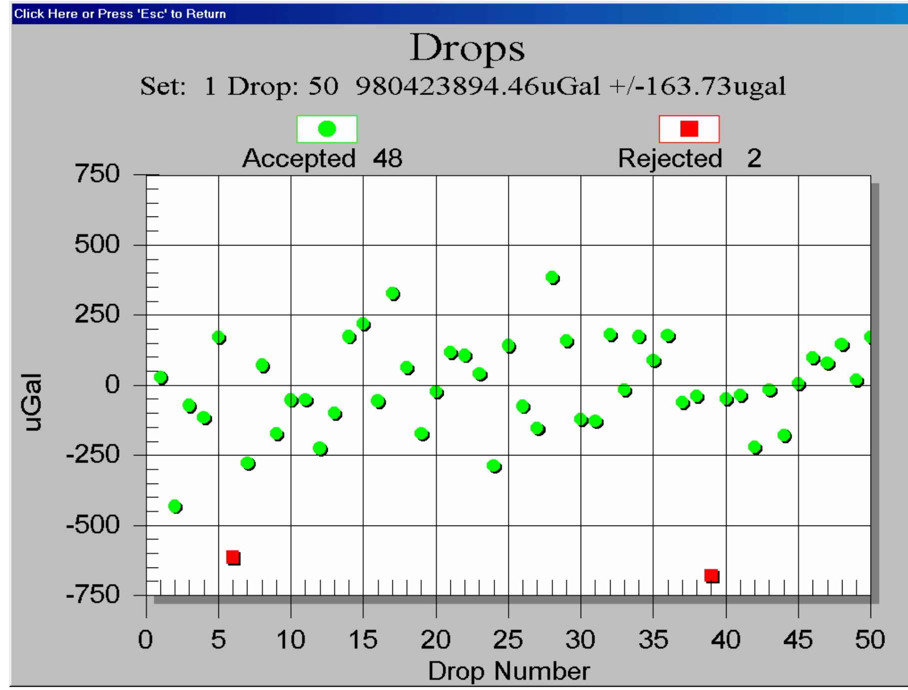


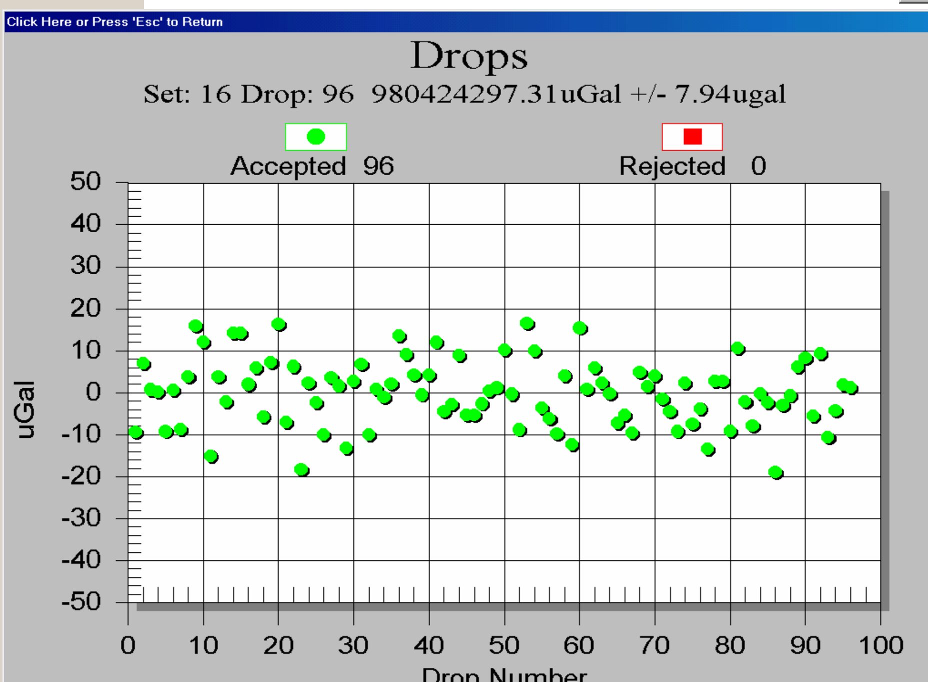
The Superspring



Measurement Scatter

Without the superspring ...





… and with the superspring

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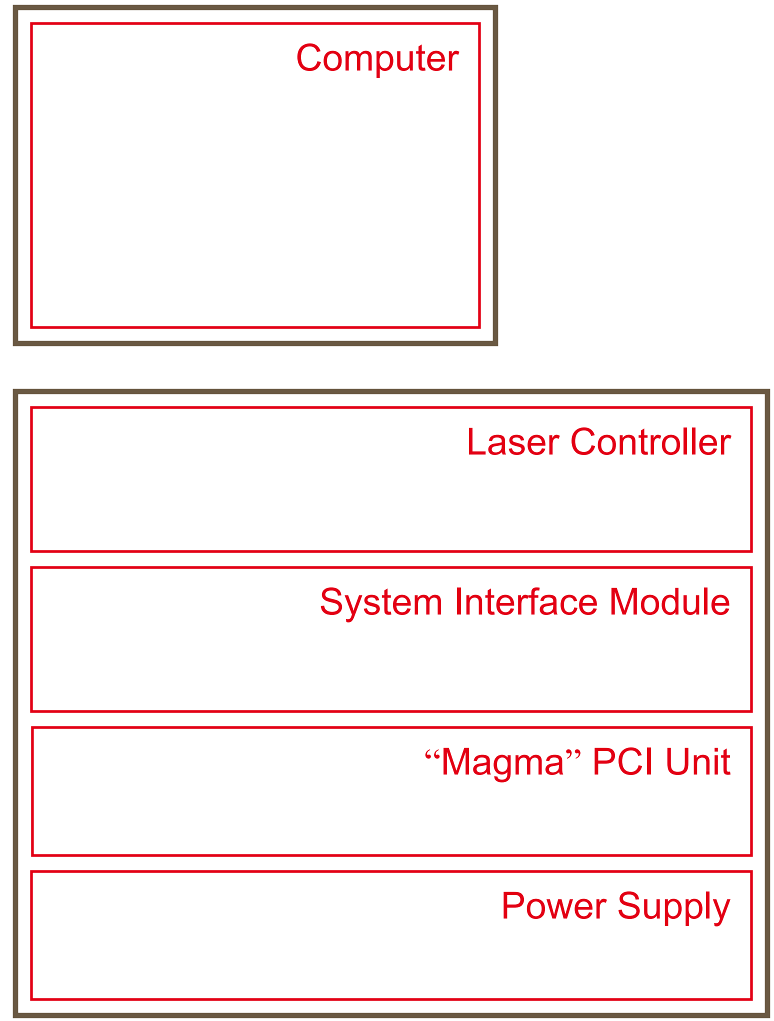
FG5 Electronics

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



WEO Iodine Stabilized Laser

- Primary Standard (BIPM Certified)
- Stabilized to rotational states (hyperfine splitting) of iodine
- Accuracy at 1 part in 10^{11}
- Automatic peak locking
- Fiber launching system
  - Faraday Isolator (prevents feedback into laser)
  - 5-axis stage
  - Polarized fiber
  - Output collimation (~6mm)
- Operating Temperature: 15 – 25 °C

FG5 Setup*

- Check Ion Pump Voltage
- Turn on WEO laser
- Level Superspring Tripod
- Measure first reference height
- Lock Superspring in tripod, level SS bubbles using feet
- Attach interferometer to top of Superspring
- Place dropper tripod on top of interferometer
- Lock dropping chamber in dropper tripod
- Decouple dropper from interferometer
- Verticalize the dropper using feet
- Measure second reference height
- Adjust beam verticality using alcohol pool
- Center Superspring position
- Optimize fringe amplitude
- Fill in parameters to software

*See FG5 User's Manual for details.

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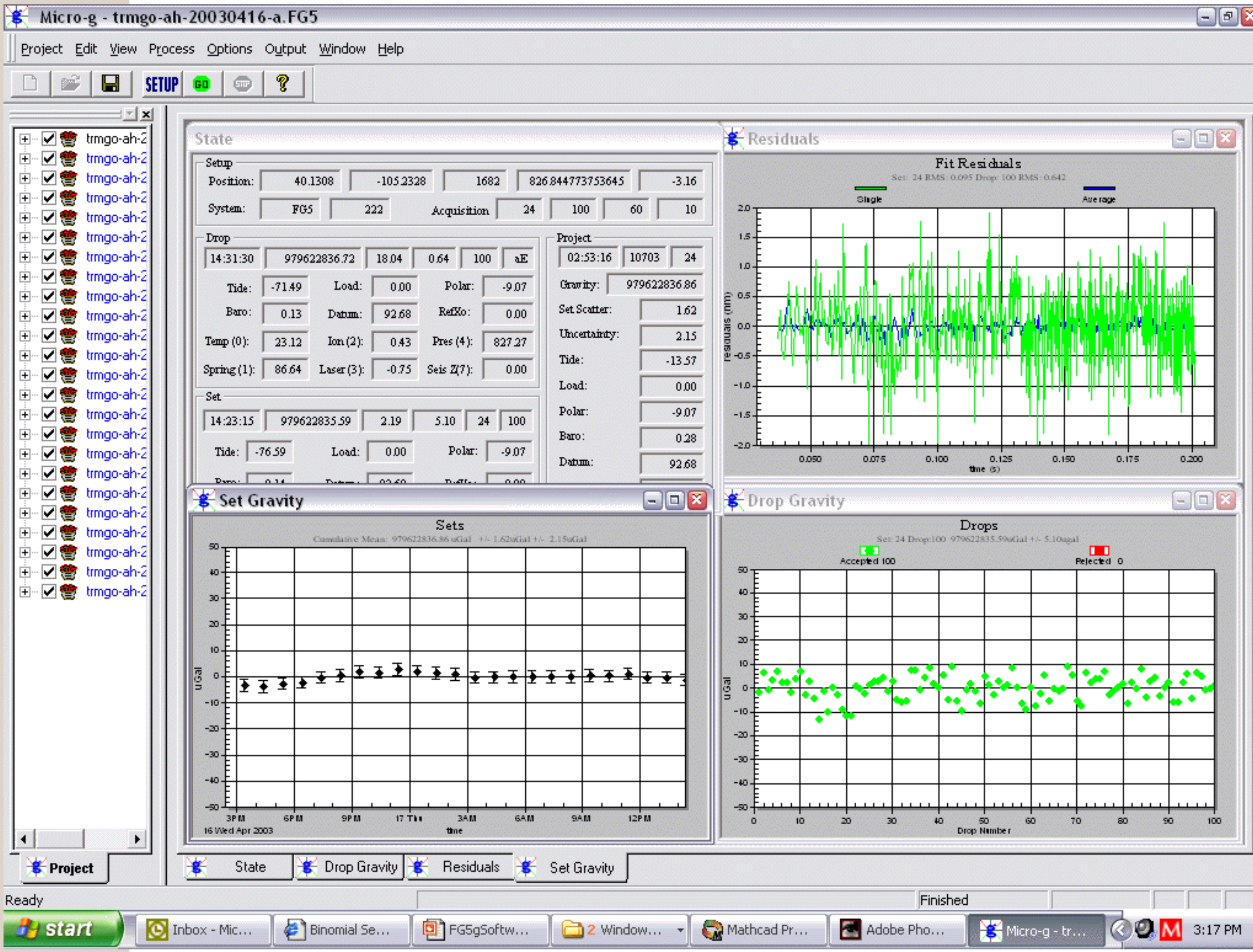
g Gravity Acquisition and Processing Software



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

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

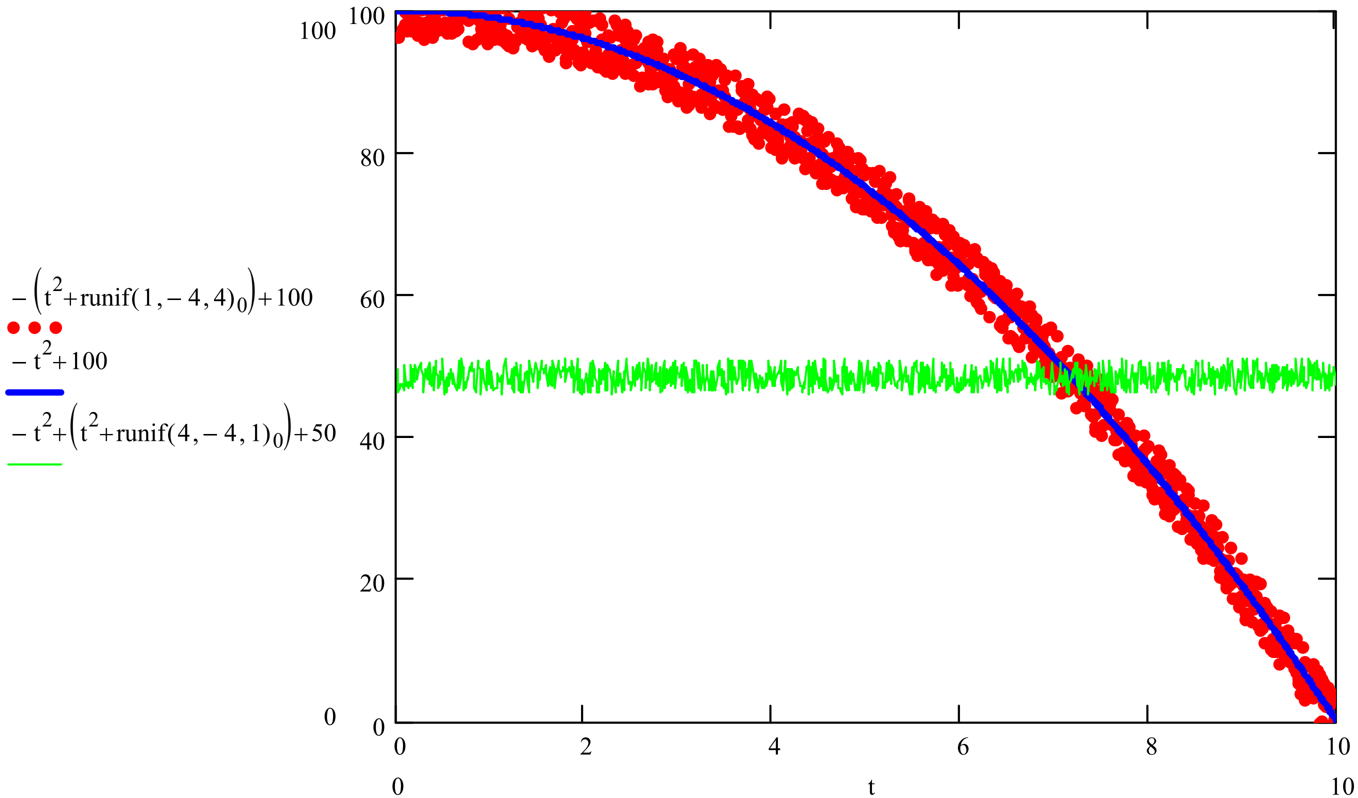
- T.M. Niebauer *et al,* Metrologia, 1995, **32**, 159-180

Prescaling & g Fit Example

Prescale*Multiplexor = 1000 #Fringes = 700

recorded fringe #	actual # of fringes	time (s) T	distance (mm) X
1	1	0.00025	0.0003
2	1001	0.0078	0.300
3	2001	0.0111	0.600
.	.	.	.
.	.	.	.
700	700001	0.207	210.000

Residuals



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

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

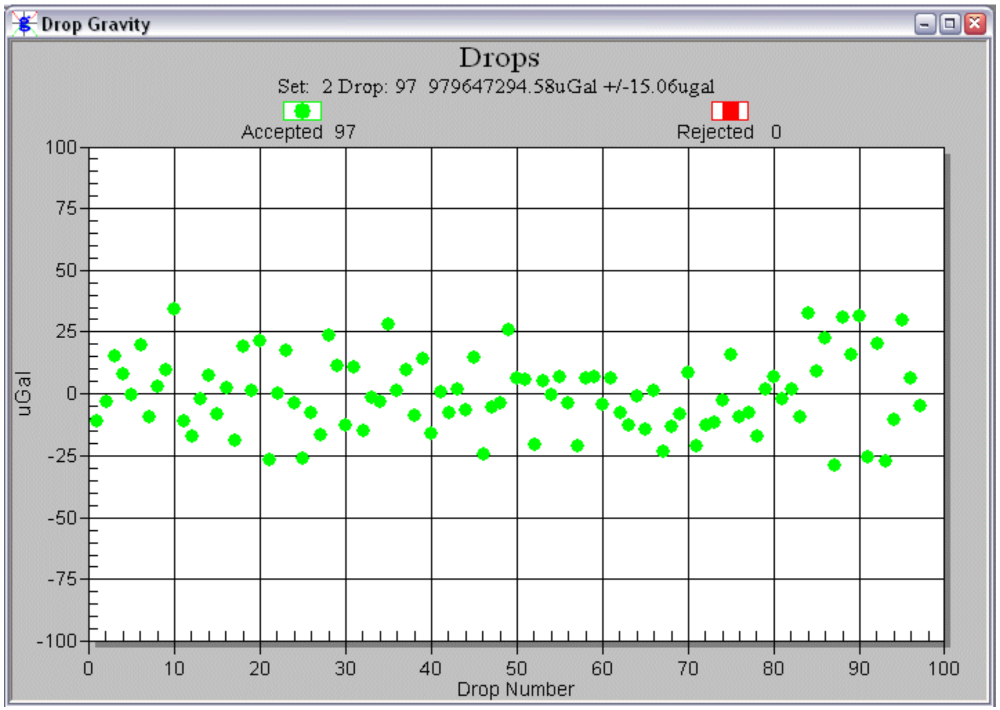
$$\delta_{total} = \sqrt{\delta_{sys}^2 + \delta_{stat}^2}$$

- 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 (12 hours or 24 hours).

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

Simple Statistics (cont)

FG5: ~2μGal Systematic Uncertainty



Example:
- Drop scatter = 15μGals
- 2μGals statistical uncertainty => ~100 drops

- For 100μGal scatter (noisy site!) => 2500 drops total
- Lifetime ~250,000 drops => 100 site occupations

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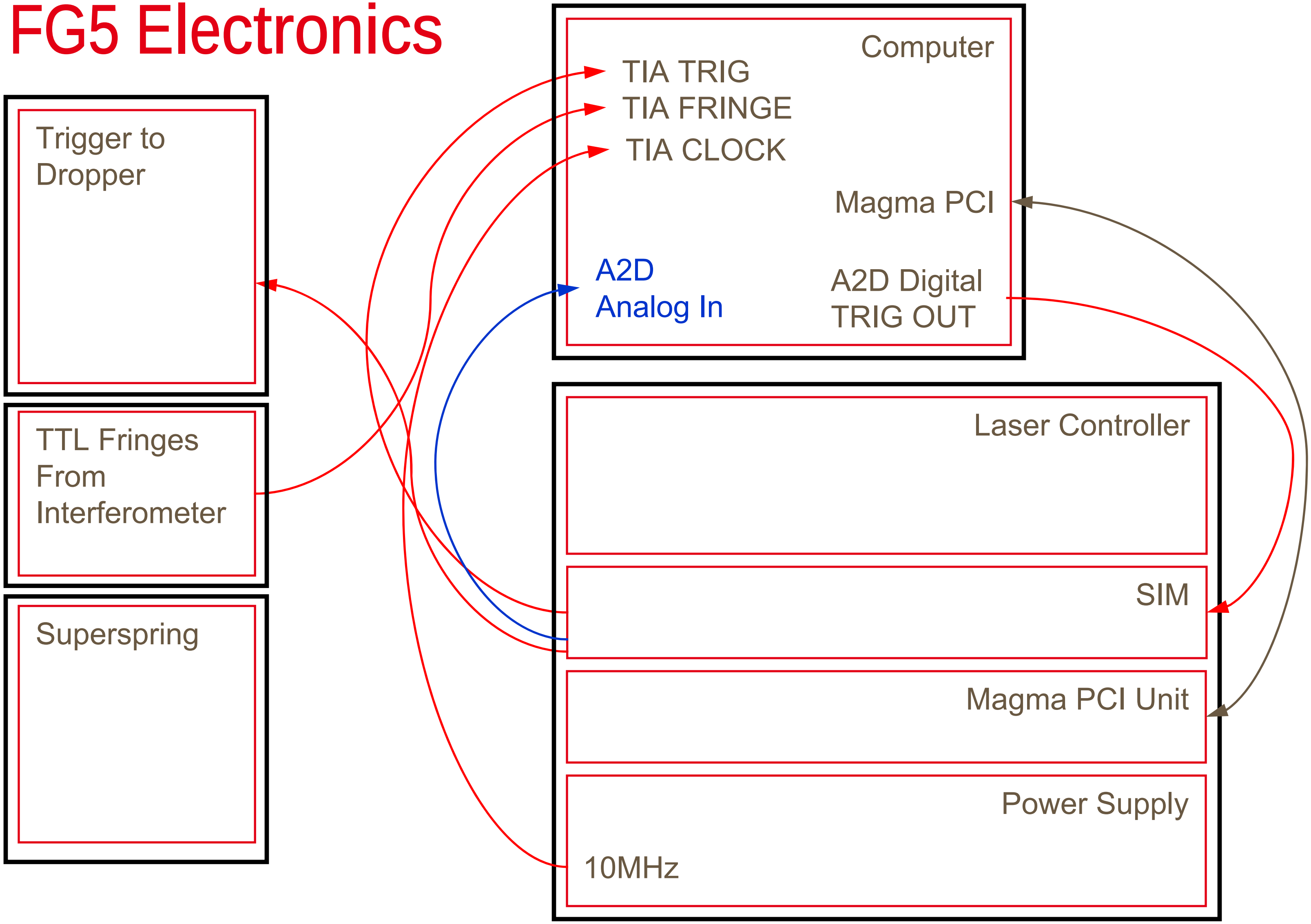
FG5 Electronics

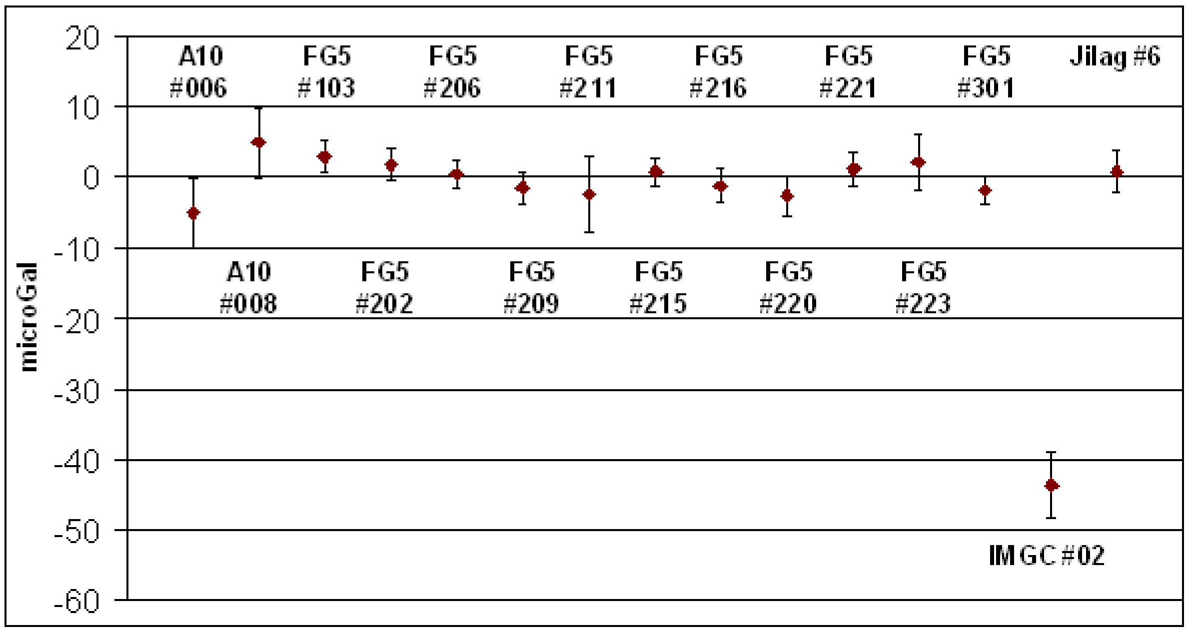


Regular Maintenance

- Regular maintenance of the system at Micro-g LaCoste is necessary
- Typically after about 250,000 drops (maximum ~500,000 drops)
- Dropper belt wear
- Optics Cleaning
- Ferrofluidic feedthrough replacement
- Ion pump degradation (plating)
- Ball & Vee wear (Micro-g)
- Laser tube degradation (Micro-g)

FG5 Results (1)

- Below are the results from a Comparison of Absolute Gravimeters in Luxembourg, 2004*
- 15 gravimeters, independent operators, 5 days
- Standard Deviation of FG5s: 2.3μGal



* O. Francis, *et al.*, "Results of the Intercomparison of Absolute Gravimeters in Walferdange, Luxembourg of November 2003," International Association of Geodesy Symposia, Vol 129, 2004.

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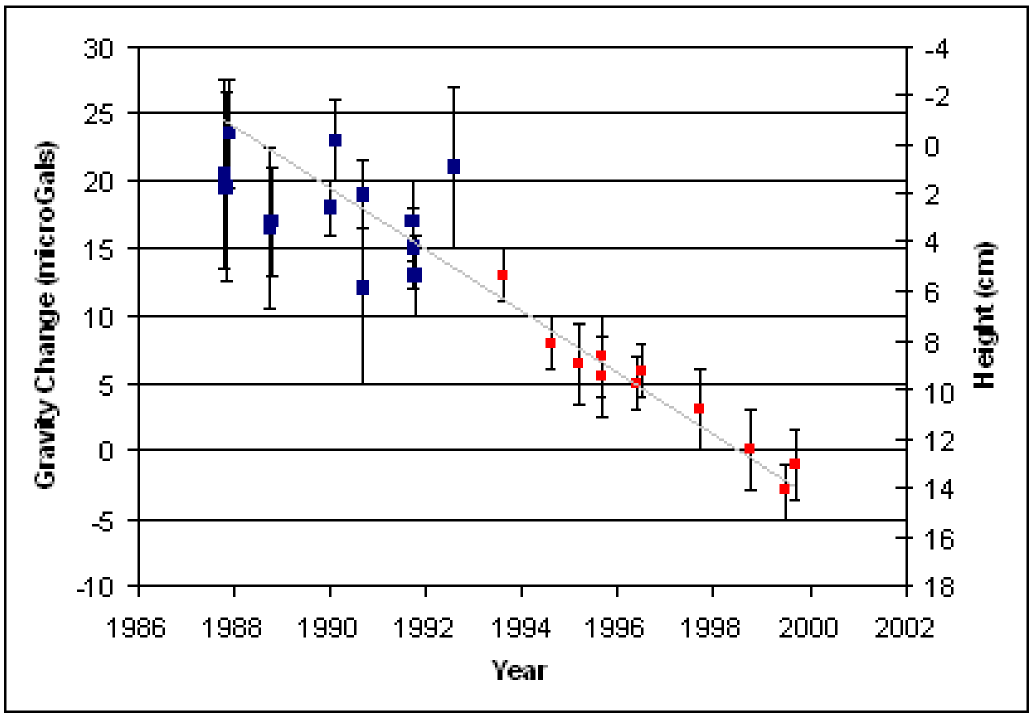
FG5 Results (2)

Shown below are the results of absolute gravimeter measurements at Churchill, Canada*. The slow reduction in gravity over 12 years is due to postglacial rebound (uplift in the crust as the earth recovers from the weight of the ice in the last ice age). This type of long-term study is only possible with the inherent stability of an absolute gravimeter



The blue squares are from JILA-g meter measurements, and the red squares are FG5 measurements.

* A. Lambert *et al.*, "New constraints on Laurentide postglacial Rebound from Absolute Gravity measurements," Geophysical Research letters, Vol 28, No. 10, pp. 2109-2112, May 15, 2001.

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