FG5 Absolute Gravimeter

Micro-g LaCoste
Derek van Westrum

www.microglacostecom
derek@microglacostecom
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 0.1 microGal in 6.25 hours]
- Operating dynamic range: World-Wide
- Operating temperature range: 15°C to 30°C
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.
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 $\lambda/2$
**g Determination**

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

\[
x_i = x_0 + v_0 \tilde{t}_i + \frac{g_0 \tilde{t}_i^2}{2} + \frac{\gamma x_0 \tilde{t}_i^2}{2} + \frac{1}{6} \nu_0 \tilde{t}_i^3 + \frac{1}{24} \gamma g_0 \tilde{t}_i^4 \]

\[
\tilde{t} = t_i - \frac{x_i - x_0}{c}
\]

- \( \gamma \) 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
- 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
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

Dropping chamber (Vacuum ~ 10^{-4} \text{ Pa} \leftrightarrow 10^{-9} \text{ atm})

- 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

Mach-Zender interferometer

Ion pump (always connected)
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)
Mach-Zender Interferometer

Michelson’s Interferometer

Mach-Zender’s interferometer: 2 beam splitters

Falling mass

B.S.

Fringes

Laser

B.S. Fringes

To other detectors

Photodiode

Fringes

Test beam

Laser

B.S.

Fallin mass

Frin ges

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

- photodetector
- twiddler
- parallelizing mirror
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

Pivots

Aneroid

Corner Cube

Coil Magnets

1st Stage Spring

2nd Stage Spring

Sphere
Measurement Scatter

Without the superspring ...

... and with the superspring
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

Diagram:

- Computer
- Laser Controller
- System Interface Module
- “Magma” PCI Unit
- Power Supply

Logos:

- FG5 Electronics
- Microg
- LaCoste
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.
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)
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
Software control

- Site Specification
- Instrument Parameters
- Data Acquisition Parameters
- Gravity Corrections
- Graphics
- Reports
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 = 1 \( \mu \text{Gal} \)
- “1 spot” = 4 \( \mu \text{Gal} \)
- Water Table: 2.5 cm = 1 \( \mu \text{Gal} \)

T.M. Niebauer et al, Metrologia, 1995, 32, 159-180
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: 2.3 µGal

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.

Prescaling & \( g \) Fit Example

Prescale*Multiplexor = 1000

\#Fringes = 700

<table>
<thead>
<tr>
<th>recorded fringe #</th>
<th>actual # of fringes</th>
<th>time (s)</th>
<th>distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.00025</td>
<td>0.0003</td>
</tr>
<tr>
<td>2</td>
<td>1001</td>
<td>0.0078</td>
<td>0.300</td>
</tr>
<tr>
<td>3</td>
<td>2001</td>
<td>0.0111</td>
<td>0.600</td>
</tr>
<tr>
<td>.</td>
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<td>.</td>
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<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>700</td>
<td>700001</td>
<td>0.207</td>
<td>210.000</td>
</tr>
</tbody>
</table>
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:
  • $\sigma = \text{drop scatter (standard deviation of measurements)}$
  • $\delta_{\text{stat}} = \text{statistical uncertainty}$
  • $\delta_{\text{sys}} = \text{systematic uncertainty (“built in” system uncertainty and model uncertainties)}$
  • $\delta_{\text{total}} = \text{sum, in quadrature, of statistical and systematic uncertainties}$

\[
\delta_{\text{stat}} = \frac{\sigma}{\sqrt{N_{\text{drops}}}}
\]

\[
\delta_{\text{total}} = \sqrt{\delta_{\text{sys}}^2 + \delta_{\text{stat}}^2}
\]

• Measure drop scatter, $\sigma$
• Pick your desired statistical uncertainty, $\delta_{\text{stat}}$
• This determines $N_{\text{drops}}$
• Spread this $N_{\text{drops}}$ over a convenient number of sets.

*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
FG5 Electronics

- Computer
  - TIA TRIG
  - TIA FRINGE
  - TIA CLOCK
- Magma PCI
  - A2D Digital TRIG OUT
  - A2D Analog In
- Laser Controller
- SIM
- Magma PCI Unit
- Power Supply
  - 10MHz

- Trigger to Dropper
- TTL Fringes From Interferometer
- Superspring