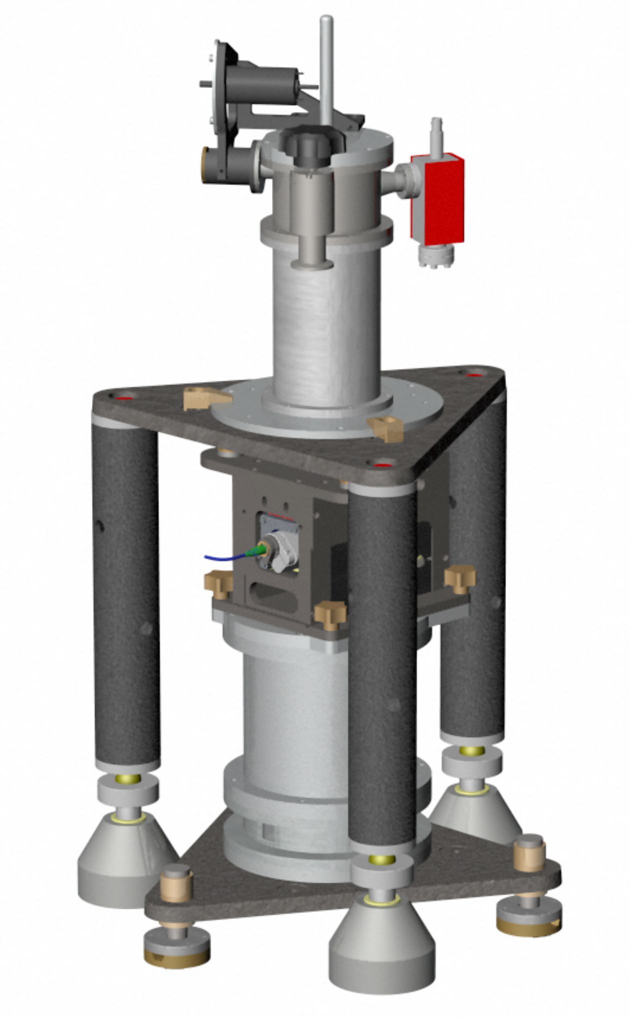
Micro g LaCoste

FGL Portable Absolute Gravimeter



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FGL OPERATOR'S MANUAL
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1 INTRODUCTION

1.1 The FGL Absolute Gravimeter

The FGL absolute gravimeter is a high precision, high accuracy, transportable, field ready instrument that measures the vertical acceleration of gravity (g). The operation of the FGL is simple in concept. A test mass is dropped vertically by a mechanical device inside a vacuum chamber, and then allowed to fall an average distance of 7cm. The FGL uses a laser, interferometer, long period inertial isolation device, and an atomic clock to determine accurately the position of the free-falling test mass as it accelerates due to gravity. The acceleration of the test mass is calculated directly from the measured trajectory.

The laser interferometer generates optical interference fringes as the test mass falls. The fringes are counted and timed with an atomic clock to obtain precise time and distance pairs. These data are fit to a parabolic trajectory to give a measured value of g. This method of measuring gravity is absolute because the determination is purely metrological and relies on standards of length and time. The interferometer uses a distance scale provided by a polarization-stabilized helium-neon (HeNe) laser. A rubidium atomic time-base provides the time scale used for the accurate timing. The value of gravity obtained with the FGL can be used without loop reductions, post processing, and benchmark ties. In addition, it is not necessary to apply tare and drift corrections normally required when using relative instrumentation.

1.2 Theory of Operation

A ballistic absolute gravimeter works by dropping an object in a vacuum and measuring the time it takes to fall a specified distance. This simple measurement has fascinated scientists since antiquity. Galileo recognized that the acceleration of a freely falling body is independent of its mass, and legend has it that he demonstrated this by dropping objects of different weight from the leaning tower of Pisa. Newton's theory of gravitation also required that the acceleration of a falling body in an external gravity field did not depend on its size, shape, or mass. Thus, measuring the acceleration of a freely falling object is equivalent to measuring gravity. This freefall acceleration is given the special symbol, g, to remind us that gravity is responsible.

The most straightforward way to measure g is to directly measure the free-fall acceleration of a test body. The measurement consists of dropping (or throwing) an object and measuring the time it takes to fall some predetermined distance. The measurements of time and distance are linked directly to the fundamental SI units of length (m) and time (s). The FGL uses a stabilized laser to provide a standard of length and an atomic clock to provide the standard time unit. Both of these units have been specified to very high precision in standard laboratories around the world. Practical realizations for both length and time are also now commercially available. This direct link to metrological standards is the necessary condition for measuring absolute gravity. The FGL inherits the stability of the length and time standards as the basis for its absolute gravity determinations.

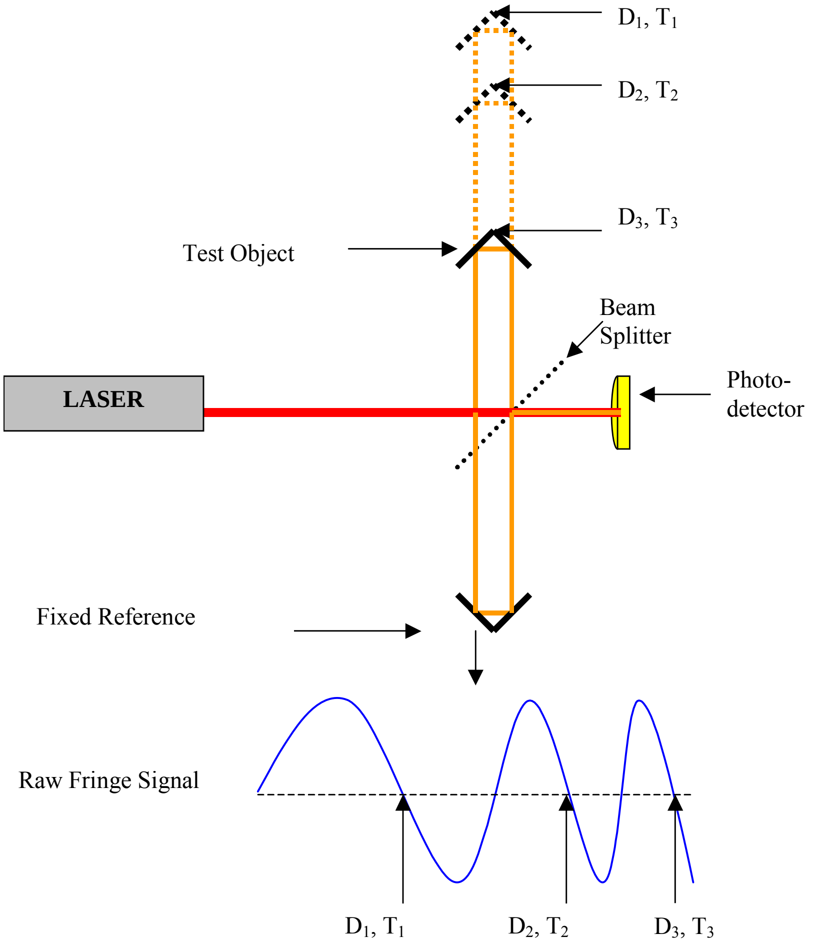

Figure 1 Direct Measurement of Absolute g

Figure 1 shows how gravity is measured with an FGL. A test body, containing a corner cube retro-reflector, is dropped from the top of the dropping chamber. A laser, with a stable wavelength, is split to reflect off the falling corner cube and a fixed corner cube which serves as a reference. The mass accelerates to the bottom of the chamber under the influence of gravity, and the raw fringe signal is detected by the photodiode as the dropped object falls. The optical fringes in the raw fringe signal are timed to create calibrated time and distance pairs. The lower part of the figure demonstrates the increase in the fringe signal frequency as the test body accelerates.

1.3 Units in Gravitational Measurements

g is defined to be the magnitude of the acceleration experienced by a freely falling body at a specified point. As such, it is simply a scalar and is reported in units of distance per squared time interval. In the S.I. system of units, gravity is nominally about 9.8 m/s^2.

Gravity is also commonly reported in the CGS system of units. This CGS unit of 1cm/s^2 is given the name Gal after the famous father of gravity – Galileo. The nominal gravity is given as 980cm/s^2 = 980Gal. Gravity measurements are often given in units of micro-gals: 1 μGal = 10^{-6}Gal. One micro-Gal (μGal) precision requires a measurement of the earth's field with a precision of 1 part in 10^9 (1 part/billion). Another common gravity unit used in field measurements of gravity is the mGal (1mGal = 1000 μGal).

1 μGal = 10^{-6} Gal.
The conversion between μGal and SI units is 1 μGal = 10^{-8} m/s^2.

1.4 Site Selection

The first step in a gravity measurement with an FGL is to identify a suitable location for the instrument. Ideal sites are located as far away from human induced noise (such as automobile and train traffic) as possible. It is best to have a site located over bedrock for stability and low noise performance. Baseline sites should be established away from fluctuating water sources such as rivers, and drainage areas.

Setting up the FGL on massive bedrock will usually provide the best results. It is important to keep the FGL out of direct sunlight and excessive, sudden temperature changes should be avoided.

1.5 Major Components of FGL

Figure 2 shows the fully assembled FGL. Major components include

- Dropping Chamber
- Dropping Chamber Tripod
- Interferometer Base or "IB"
- Superspring
- Superspring Tripod
- Cables
- System Electronics
- Shipping/Deployment Cases
- Laptop Computer – PCI Unit
- Turbo Pump

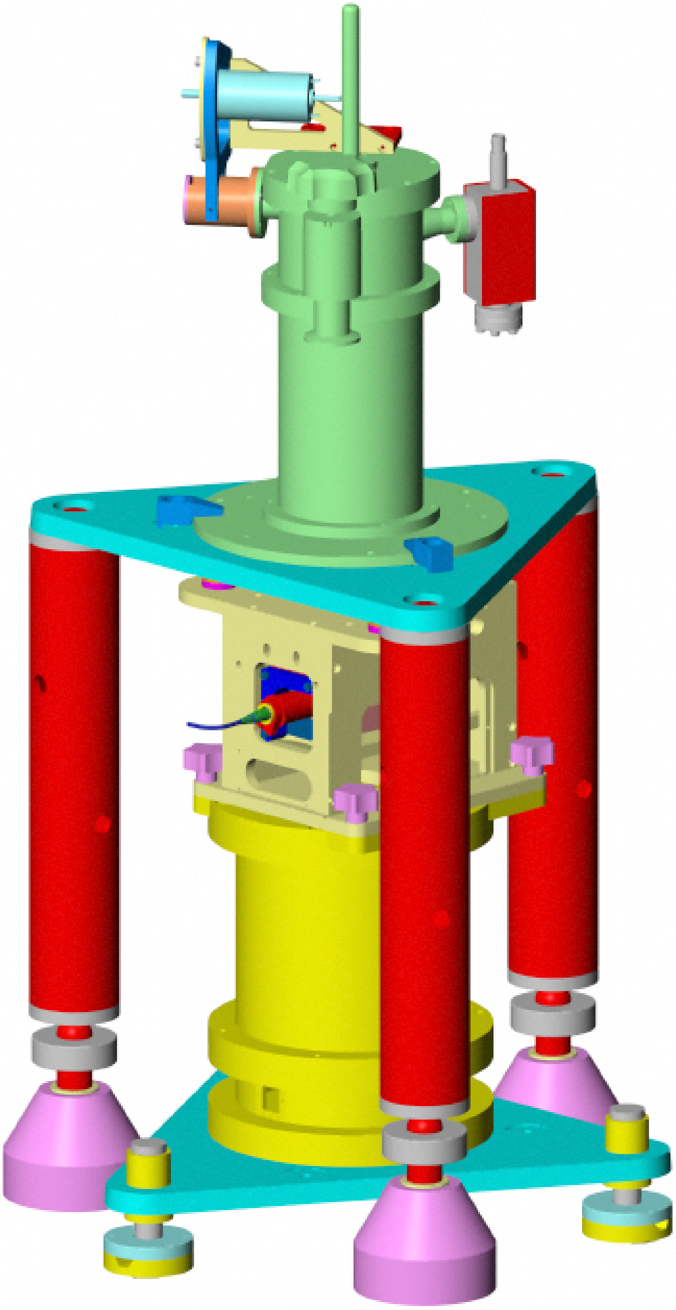

Figure 2. FGL Schematic

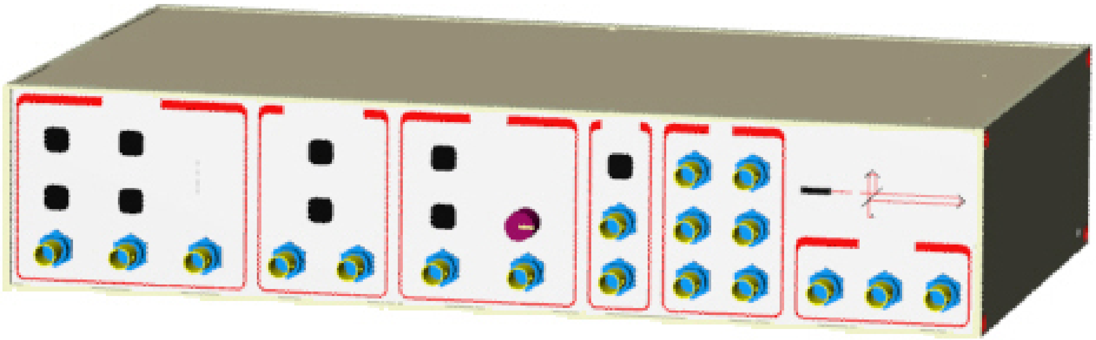

Figure 3. System Interface Module (SIM) – includes Dropper Controller, Superspring Controller and Analog/Digital I/O (A2D).

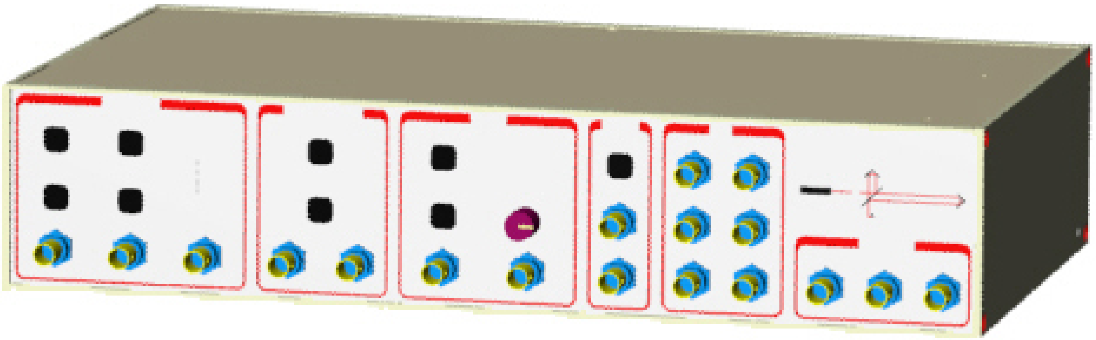

Figure 4. Electronics Rack, rear view. Top to bottom: Control Panel, Patch Panel, Dropper Controller.

2 DETAILED THEORY OF OPERATION

2.1 Superspring Theory

The Superspring is a long-period, active, seismic-isolation device designed to keep the reference corner-cube from experiencing high frequency vertical ground motions. This insures that any change in the length of the test beam is due only to the acceleration of the dropped object.

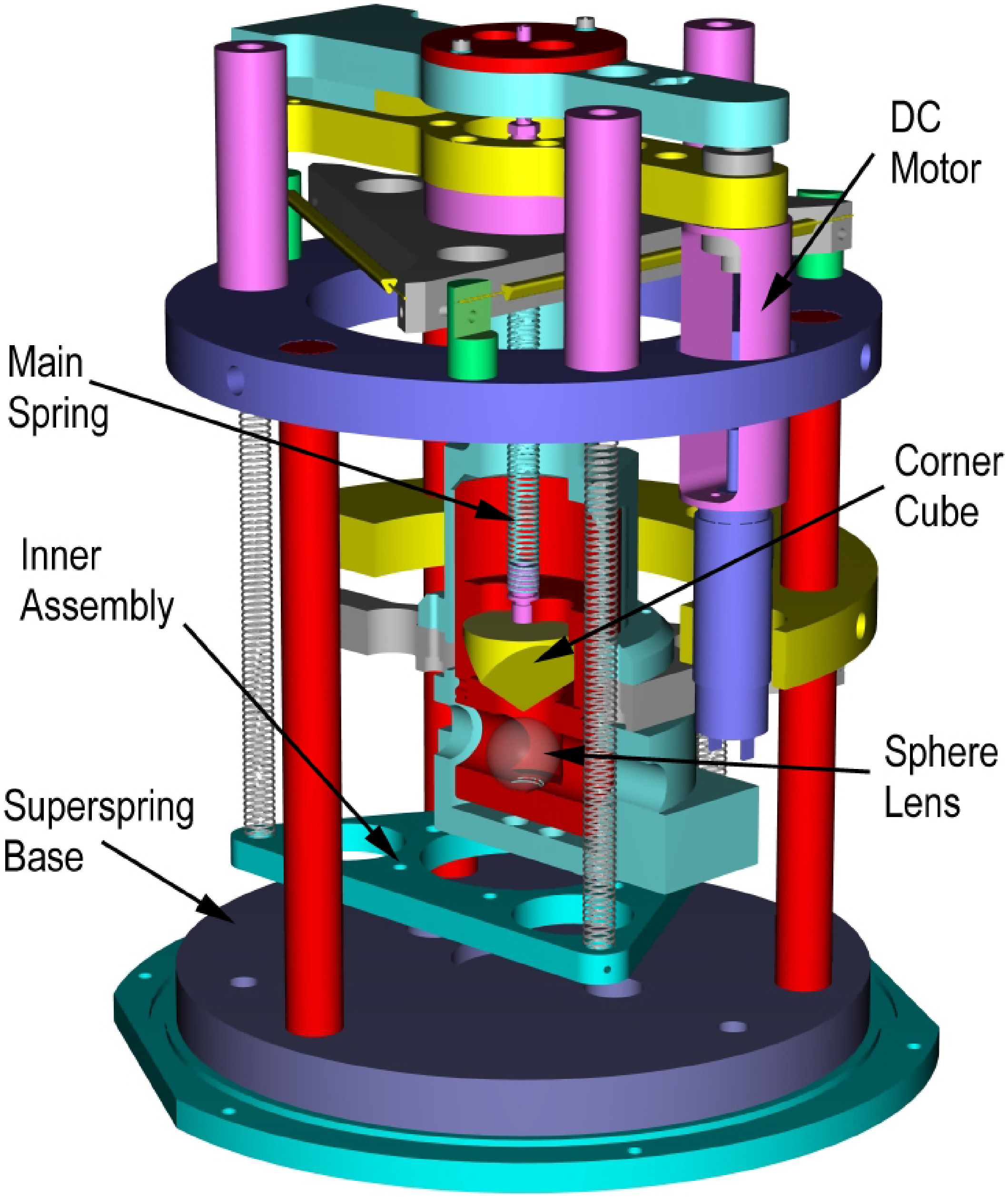

Figure 5. Superspring Schematic

The superspring is a double-stage spring system. A schematic is shown in Figure 5. An inner support assembly hangs from the superspring base structure on three short springs. Hanging from this inner support assembly is the mainspring, which holds the superspring test-mass/corner-cube. This mainspring is approximately 10 cm in length and has a natural frequency of about 2 Hz. The inner support assembly is actively servo-controlled to track the vertical location of the superspring mass. By keeping the length of the mainspring as constant as possible, the resulting system has a period of approximately 30 seconds. The superspring is thus able to isolate the test mass from ground motions occurring at frequencies higher than this.

The servo mechanism works as follows. The superspring sphere detector system senses motions of the superspring mass relative to the inner support housing. An infrared light emitting diode (LED) located on the support housing directs light through an optical glass sphere attached to the superspring mass. The sphere focuses this light onto a split photodiode detector mounted on the opposite side of the support housing. This signal from the split detector is fed back to a servo circuit which drives the support housing vertically, canceling any relative motion between the test mass and the inner housing. The drive mechanism is a linear coil actuator mounted between the support housing and the superspring base. So as vertical ground motion occurs, the linear actuator moves the support housing up or down in such a way as to keep the main spring length constant. This active servo effectively weakens the main spring, synthesizing a long period isolation device. The apparatus is constrained to move only vertically by a linear system constructed of five flexures (delta rods) arranged in an upper V-shaped array, and a lower triangular array.

For details on Superspring operation, please the “SIM” Manual. Briefly, however: The servo circuit is activated by activating SERVO on with the SIM controller. Note that if SERVO is off and the spring is un-travel-locked, the spring is just hanging freely and bouncing with the system’s natural frequency (about 2 Hz).

The Superspring system also contains a DC motor that is used to center the test mass vertically in its range---“zeroing the spring” (as described in the Setup instructions above). The position is converted to a voltage, and the range is approximately ±1 V. If the position is more than about 0.1 V away from zero, then the Superspring should be re-centered. To do this, simply press ZERO on the SIM controller.

Temperature fluctuations will change the length of the spring, and the position should be checked at the beginning of each measurement. Also, note that if the gravimeter has moved to a location with a drastically different local gravity value than the previous measurement location, it might take a few minutes for the spring to get to this zero position. This is normal.

2.2 Dropping Chamber Theory

2.2.1 The Dropping Chamber

The Dropping Chamber is an evacuated chamber which contains the drag-free cart which, in turn, houses the test-mass/corner-cube. Figure 6 shows a schematic. A drive mechanism is used to drop, track, and catch the test mass inside the drag-free chamber. Laser light passes through a window in the bottom of the Dropping Chamber to the corner cube (inside the test mass), and is then reflected back down through the window to the interferometer.

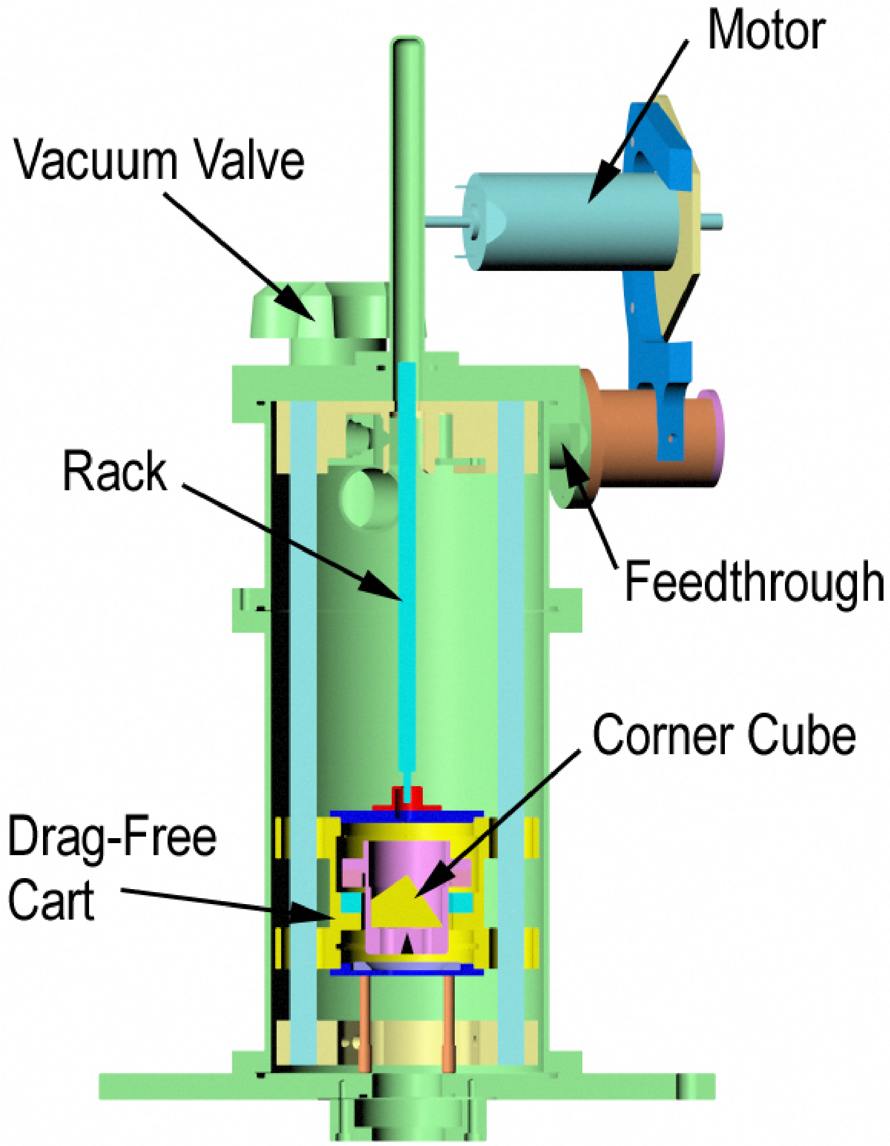

Figure 6. Dropping Chamber Schematic

The drag-free cart is used to lift, drop, and catch the test mass. The term "drag-free" refers to the fact that though the chamber is evacuated, there are still some residual air molecules. The cart effectively pushes these molecules out of the way of the test mass, which is falling behind the cart. In addition to reducing drag, the cart also reduces magnetic and electrostatic forces on the test mass.

At the beginning of a drop, the cart accelerates downwards with an acceleration greater than g. Once a certain separation between the cart and the test mass is reached, the cart slows down and tracks the test mass, maintaining a constant separation of a few millimeters. Finally, at the bottom of the drop, the cart gently catches the test mass. By keeping track of the cart position using a shaft encoder, and using the interferometer (fringes) to establish the test mass position, the distance between the cart and the mass can be determined. (For historical reasons this is referred to as "sphere detection".) During freefall, this separation is maintained at a constant distance by using a servo-motor drive system to control the cart inside the Dropping Chamber.

The test mass contains a retro-reflective corner-cube surrounded by a support structure which is balanced at the optical center of the corner-cube. The corner-cube is a three-surface mirror which has the special optical property that the reflected beam is always parallel to the incident beam. In addition, the phase shift of the reflected beam is virtually constant with respect to any slight rotation or translation of the corner cube around its optical center. When in contact with the cart, the corner-cube is supported by three spherical feet (or "balls") that fit and orient it to "vees" in the cart.

The drive mechanism is a support structure inside the dropping chamber on which the cart/drag-free chamber travels up and down, and is driven by a DC servo motor. The cart is attached to a rack that is driven up and down by a shaft attached to the motor. The motor is located outside of the chamber is connected to the shaft via a ferrofluidic feedthrough. The motor also turns an optical shaft encoder that provides accurate information to the dropper controller on the position and velocity of the pulley.

2.2.2 The Dropper Controller

The dropper controller ultimately controls the motor that drives the cart. It is also the interface between the user and the dropping chamber. It houses the circuitry that uses the sphere feedback system to control the cart position. The dropper controller is located in the System Interface Module (SIM) – please refer to that operator's manual for details of operation.

The dropper controller uses two modes to operate the dropping chamber. These modes are OSC and DROP.

In DROP mode, the controller directs the motor of the dropping chamber to lift the cart and test mass to a specified height, to move the cart at a specified velocity, and to track (maintain a specified separation distance) the test mass during free-fall. To initiate a drop, make sure the dropper is un-locked, place the controller in DROP mode, and press the TRIGGER button. This will lift the cart to the top. Press TRIGGER again. This will cause a freefall drop of the test mass. To stop DROP mode, press TRIGGER until the cart is at the bottom position (note the LEDs that indicate the current cart position), and then press RESET. The controller is now insensitive to triggers.

OSC (oscillation) mode is used to slowly raise and lower the cart (the object is never in freefall) to create slow and constant interference fringes. The magnitude of this fringe signal is used for system alignment purposes. To initiate OSC mode, first make sure the dropper is un-travel-locked, and the press OSC. You should see the position LEDs on the front of the controller indicate a slow movement of the cart. To stop OSC mode, press the TRIGGER or DROP button at any time. The cart will automatically stop at the bottom of the next oscillation cycle. Take care not to hit the RESET button directly, as this will drop the cart to the bottom and can cause excessive wear on the ‘balls’ and ‘vees’.

2.3 Interferometer Theory

Refer to Figure 7 and Figure 8 for the following description of the beam path. The optical fiber directs the laser light from the laser head to the interferometer base. At the input of the interferometer, a lens collimates the light from the optical fiber. It is then directed to beamsplitter #1, where it is split into a test beam and a reference beam. The reference beam is split again at beamsplitter #2 and travels to the Avalanche Photo Diode (APD) and the fringe viewer. The path length of the reference beam remains constant.

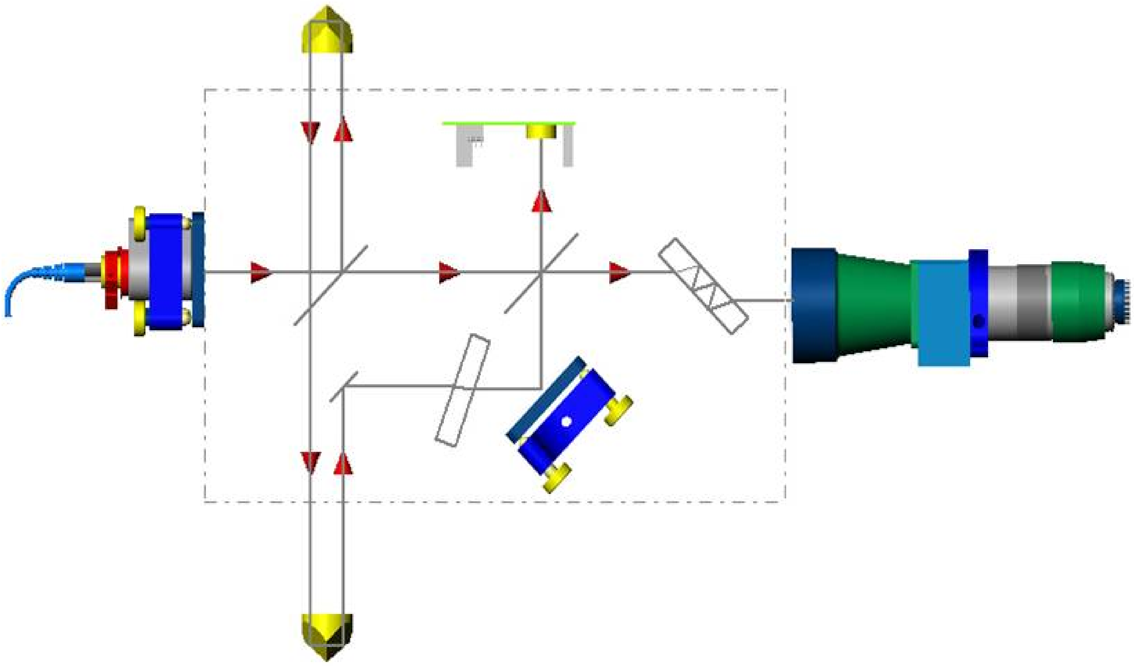

Figure 7. Beam path in FGL interferometer. Light from the optical fiber is split at Beamsplitter #1 in a vertical test beam and a horizontal reference beam. The beams are recombined at Beamsplitter #2 and sent to the photodetector and user optics for alignment purposes.

The test beam is reflected upward at beamsplitter #1, passes through the Dropping Chamber, and is then reflected back down by the corner cube in the test mass. The test beam returns through the interferometer and down into to the superspring. It is then reflected back up by corner cube in the superspring mass. The test beam reflects off mirror #1 (the "pick off" mirror), passes through the translator plate (twiddler), reflects off mirror #2, and is recombined with the reference beam at beamsplitter #2.

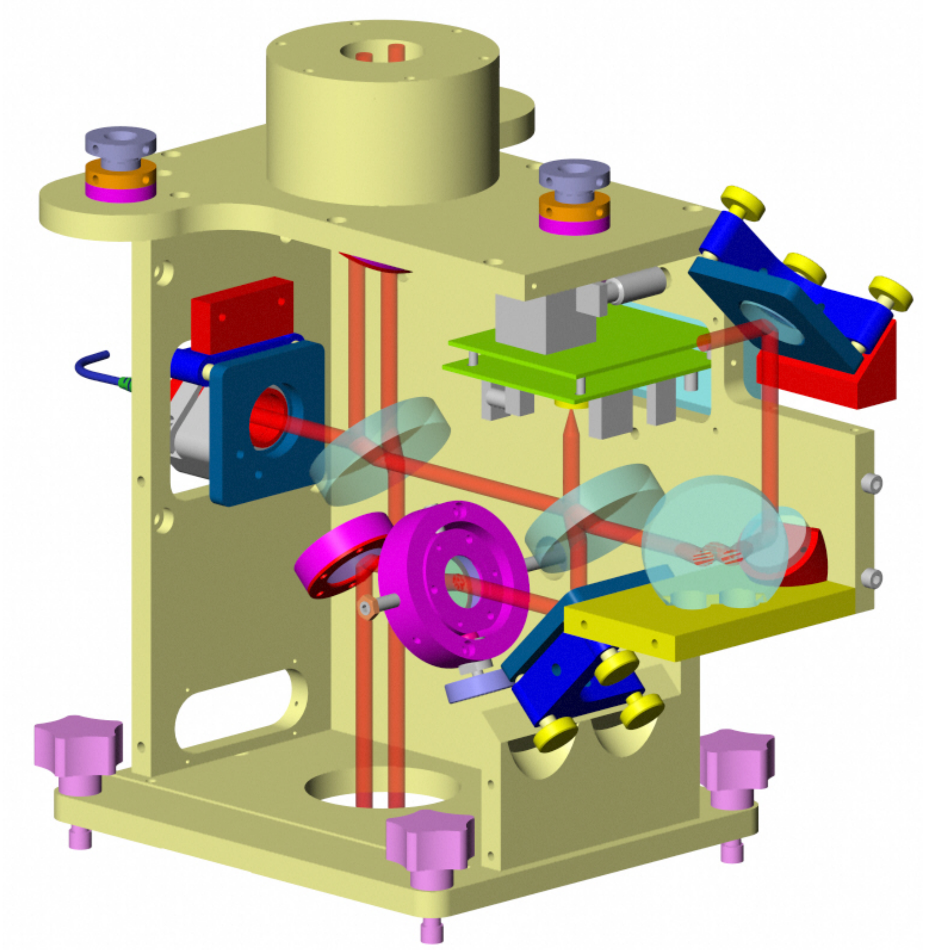

Figure 8. Schematic of FGL interferometer

This interferometer is a Mach-Zender interferometer with a fixed (reference) arm and a variable (test) arm. During a drop, the motion of the test mass/corner cube affects the path length of the test beam. The interference fringes which result from the recombination of the test beam and the reference beam provide an accurate measure of the motion of the test mass relative to the mass suspended on the superspring.

The reference and test beams are recombined at beamsplitter #2. The vertical portion of the recombined beams is focused by a lens to strike the detector (APD). and the interference fringes are converted to an analog and a digital (Transistor Transistor Logic [TTL]) signal and transmitted to the time interval analyzer.

The other portion of the recombined beam travels horizontally and is used by the operator to precisely align the interferometer (see Section 3 for more information).

2.4 Laser Theory

The FGL employs a Micro-g LaCoste model ML-1 HeNe, polarization-stabilized laser. For detailed theory and operation, please refer to the ML-1 operator’s manual. The ML1’s frequency stability is obtained by balancing the intensities of two TM00 modes in the laser tube. These two modes have orthogonal linear polarizations, allowing them to be separately detected by independent photo-detectors using polarizing optics. The length of the laser cavity is adjusted by changing the temperature using a heater wrapped around the laser tube. Figure 9 shows a schematic. This variation in length affects the intensities of the blocked and passed polarizations which alternately vary from a minimum to a maximum level as seen in Figure 10. The difference (blocked-passed) signal is used to lock the laser cavity length. There are two possible lock points (two different wavelengths) denoted in Figure 10 as “red” and “blue”. Note that the designation of “red” and “blue” are arbitrary choices and do not denote the actual differences in wavelength.

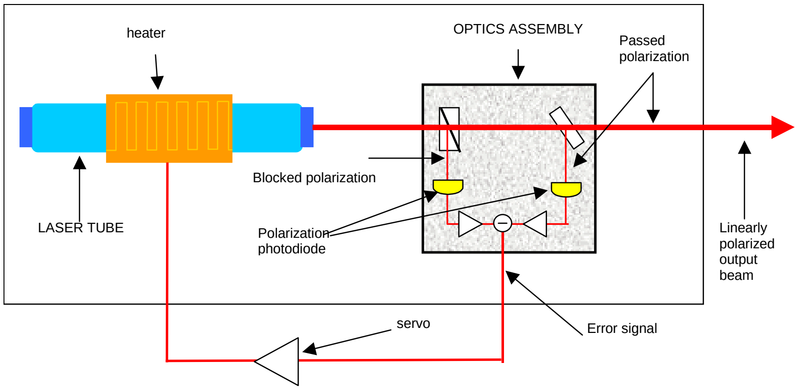

Figure 9. ML-1 Schematic. The intensity of two polarizations is monitored and fed-back to a heater that determines the cavity length.

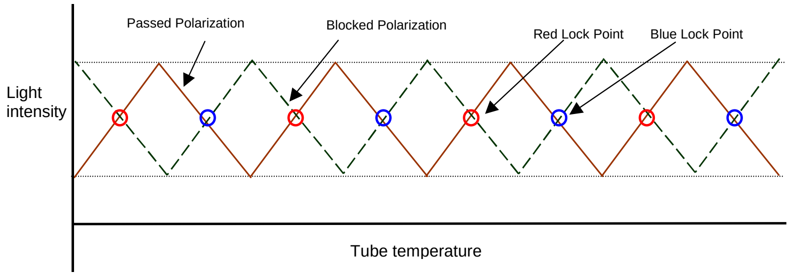

Figure 10. Intensity of the two polarizations as a function of temperature.

The laser cavity takes approximately 1 hour to warm up to its nominal, equilibrium length. At this point, the laser can be “locked” into either one of its two modes. With REMOTE mode off (manual mode) the laser is locked by turning the selector switch to either RED or BLUE. When not acquiring data, it is best to let the laser go back into “warm-up” mode (LASER LOCK off), so as to let the cavity length maintain equilibrium. With REMTOE mode enabled, the *g* software performs this locking/warm-up automatically. Note that it is normal for the laser power (and therefore fringe amplitude) to fluctuate when the laser is not locked.

Temperature fluctuations can cause the laser frequency to fluctuate by hundreds of MHz. Therefore the laser is located in a separate chamber that is temperature controlled to a fraction of a degree C. It is important however, to not take data until the laser has reached its thermal equilibrium (indicated by a blinking light on the laser head – again please refer to the ML-1 operator's manual).

As mentioned, the laser light reaches the interferometer via a polarized optical fiber. The light enters this fiber through a 5-axis mount. This mount allows the fiber to match position of the laser beam (2-axes), the angle of the laser beam (2-axes), and the focus of the laser beam (1-axis). It also allows the input end of the fiber to be rotated so that the fiber's polarization matches that of the laser light. See Section 4.2.3 for details on the 5-axis mount and fiber rotation. This adjustment is difficult and is only performed in rare situations.

Finally, optical feedback of laser light reflected or scattered back into the output aperture can seriously degrade the stability of the ML-1. The FGL uses a Faraday optical isolator to minimize feedback. Dust, dirt, and fingerprints on the laser optics can also lead to unreliable operation due to scattering and feedback. Though the laser chamber is sealed, it is important to keep the laser chamber clean and dust-free.

3 FGL SETUP

3.1 Instrument Assembly

Locate and mark a reference point on the floor where gravity will be measured. The floor should be as clean, smooth, and level as possible. It is best to set up the FGL on a concrete pier or hard tile floor.

These instructions assume that the dropping chamber is already at a high vacuum level. See Section 5 for instructions on pumping out the dropping chamber.

3.1.1 Electronics Case

For a full discussion of the FGL electronics, please refer to the SIM instruction manual.

- Place the electronics case in a convenient location about 1 meter from the reference mark. Check the input voltage settings and make sure they are set to the proper AC line voltage. All standard components of the FGL gravimeter accept 100-240 VAC, 50/60 Hz.
- Make sure the following switches are off:
- Main AC power (Power Supply rear)
- Main DC power (Power Supply rear)
- Laser power (both main AC power and key switch)
- If the ion pump has been maintaining the dropper vacuum on battery power, open the dropping chamber case and apply AC power to the ion pump power supply. See Section 5 for more details on the ion pump controller.
- Open the Interferometer case, and place the laser on the floor about 1 m from the reference mark. Take care not to stress the fiber optic.
- Connect the main AC power cable from the FGL power supply (rear of electronics case) to the AC power receptacle. If an uninterruptible power supply is to be used with the FGL, it should be connected to the main AC power source and the FGL AC power supply should be connected to the UPS output.
- Turn on the main AC and DC power switches on (rear of electronics case).
- Connect the applicable cables to the laser and turn on the laser power. Consult the manual appropriate to the laser you are using.

3.1.2 Setting up the Superspring Tripod

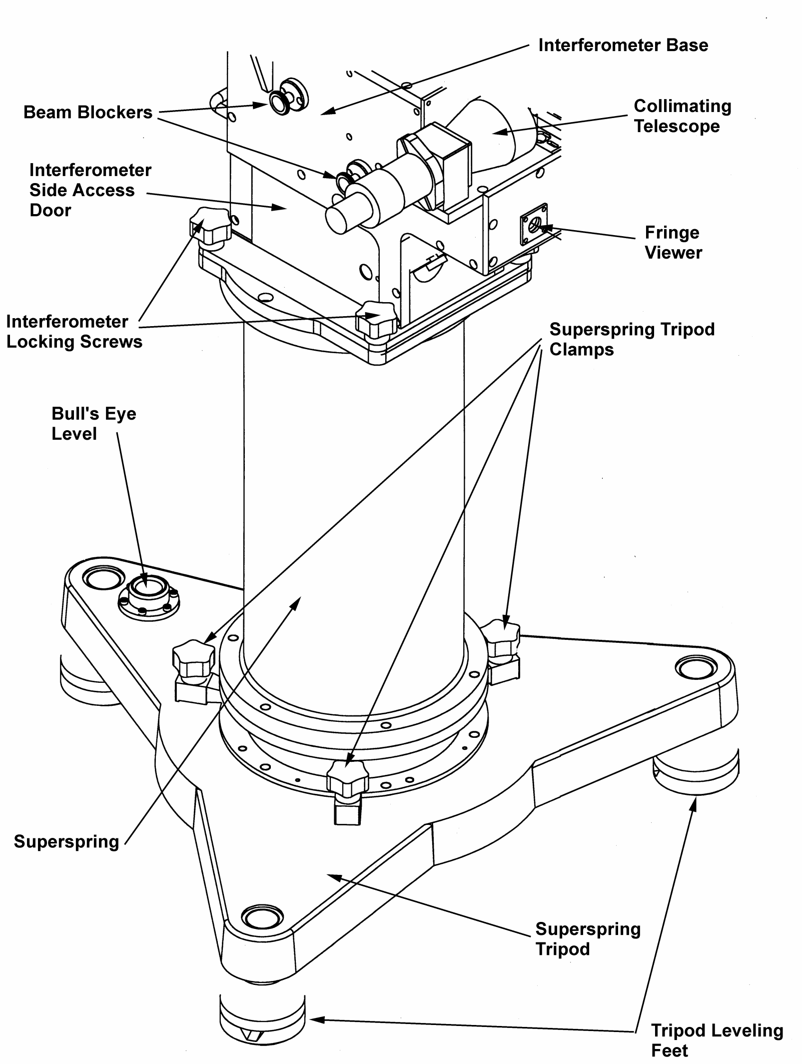

Figure 11. Superspring/Interferometer Setup

Figure 11 illustrates the location of the Superspring and interferometer base for setup.

- Remove the superspring tripod from the interferometer case and place on the floor over the reference mark. Orient the tripod so the bull's eye level (mounted near one of the leveling feet) is facing the electronics case, if possible. A line from the bull's eye level to the center of the tripod should be aligned North-South to minimize Coriolis accelerations of the dropped object. The tripod can be centered over the mark by viewing the mark through the hole in the center of the tripod.
- Rough level the superspring tripod using the bull's eye level.

- Measure the lower reference height using the depth gauge provided. The lower reference height is the distance between the superspring tray ring and the reference mark (approximately 5-15 cm). Place the depth gauge parallel surface on the machined inside ring of the superspring tripod. Pass the gauge rod through the hole in the center of the superspring tripod and extend it until it hits the reference mark on the floor. Tighten the locking screw and measure gauge length using the scale fixture which is used to measure the upper reference height (see below). Record this value in the system check log.
- Place the superspring on the tripod. Orient the superspring so the travel lock (brass knurled knob on the service ring) is pointing toward the bull's eye level.
- Clamp the superspring to the tripod by turning the three 5-lobe knobs fully clockwise. This rotates the clamps in place over the base of the superspring.
- Level the tripod using the two precision level vials on the base of the superspring. Be sure to adjust the cross level first, then the long level. The cross level is opposite the superspring travel lock (knurled brass knob). If the long level is adjusted first, it will change when the cross level is adjusted. When the cross level is adjusted first, it does not change when the long level is adjusted. Only turn two of the feet while leveling; this insures that the lower reference height does not change

Note: While leveling the superspring and dropping chamber tripods, note that turning the tripod feet clockwise ***lowers*** the dropping chamber tripod and ***raises*** the Superspring tripod.

3.1.3 Interferometer

- Remove the interferometer base from its shipping case taking care not to stress the fiber optic. Remove the dust cap from the top superspring window and place the interferometer base on the superspring. Orient the interferometer base so the fiber optic input is located directly above the superspring travel lock. The alignment pins on the top of the superspring assure that the interferometer base is oriented correctly.
- Lock the interferometer base in place by tightening the four 5-lobe knobs.

3.1.4 Dropping Chamber Tripod

- Remove the tripod tray from the Superspring case and place it carefully upside-down on the floor.
- Remove the three tripod legs from the dropping chamber case and attach them to the tray. If necessary, tighten the legs by using the ~30 cm "cheater" bar.
- At this point the interferometer will be used to support the dropping chamber tripod. First, remove the dust cap from the top of the interferometer base.
- Carefully place the dropping chamber tripod on the interferometer. Orient the tripod so that the small hole is above the Superspring travel lock and laser fiber.

- Carefully remove the dropping chamber from its case and gently place it into the pocket in the top of the tripod tray, allowing the two vertical alignment pins in the tray to engage the sockets in the dropping chamber base. Orient the dropping chamber so the tripod toe clamps align with the brass nodes on the dropping chamber. See Figure 12.

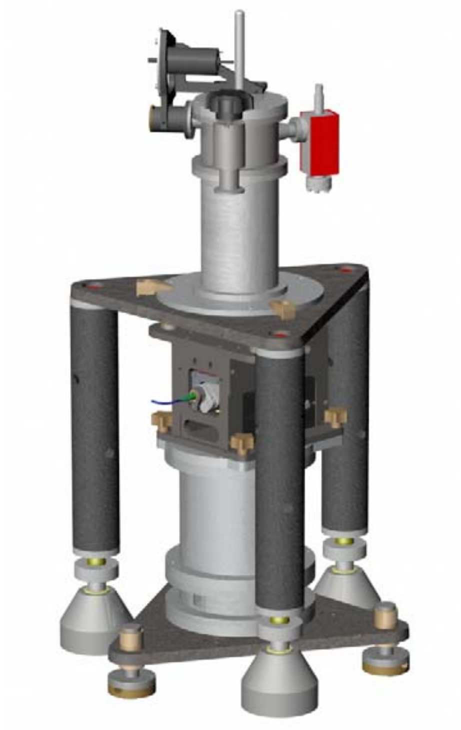

Figure 12. Orientation of the dropping chamber in the tripod.

- Lock the dropping chamber in place with the three clamps by turning the 5-lobe know fully clockwise. This rotates the dropping chamber clamps in place over the base of the chamber.
- Release the cart travel lock by turning the motor shaft slightly counterclockwise with a 4 mm hex wrench to release the pressure on the travel lock mechanism. While holding this position, pull out on the knurled knob, rotate it 90º in either direction, and gently release it so the pin is not engaged on the motor shaft.

3.1.5 Leveling the Dropping Chamber

Note: While leveling the superspring and dropping chamber tripods, note that turning the tripod feet clockwise *lowers* the dropping chamber tripod and *raises* the superspring tripod

- Check the superspring levels and adjust, if necessary, by leveling the superspring tripod
- When the superspring levels are centered, the dropping chamber tripod levels should be within two divisions of the center position. If the levels do not agree,

this may indicate a problem. Consult the section on adjustment and maintenance for instructions.

- Remove the blue pads and brass tripod feet from the superspring case. Make sure the pads and tripod feet are clean.
- Place a tripod foot under each leg of the tripod. Raise each foot and slide a blue pad under the foot.
- Center the cone in each foot under the nylon ball on the end of each tripod leg. Turn the leveling adjustment screws on the feet counterclockwise, raising them until they just barely contact the balls. It is important that there is no horizontal tension between the foot and the tripod leg because it will cause the dropping chamber to shift sideways when it is lifted. It is helpful to rotate, or wiggle, the foot slightly (while it is in contact with the nylon ball) to release any horizontal tension.
- After each foot is in contact with the tripod leg, rotate each tripod foot leveling screw one revolution (counterclockwise), using the mark on the top of the adjustment screw as a reference. Then, rotate each tripod foot leveling foot one additional revolution as described previously. The two total turns raise the tripod off of the interferometer so there is no contact between the two components. Each counterclockwise revolution of the leveling screw raises the tripod about 0.75 mm
- Level the tripod tray by adjusting the dropping chamber tripod feet (not the superspring tripod legs). Be sure to adjust the cross level first, then the long level. The cross level is parallel to the telescope and the long level is perpendicular to the telescope. If the long level is adjusted first, it will change when the cross level is adjusted. When the cross level is adjusted first, it does not change when the long level is adjusted.
- It is best to adjust the levels by raising the proper adjustment foot. This will prevent the dropping chamber from contacting the interferometer.

Note that there must be no contact between the tripod-dropping chamber assembly (and their cables) and the interferometer/superspring assembly (and their cables) during the measurement.

- Check the superspring levels and adjust, if necessary, using the leveling feet on the superspring tripod
- Measure the upper reference height using the scale fixture provided. The upper reference height is the distance between the top of the interferometer base and the bottom of the dropping chamber. Loosen the clamp on the scale and pass the scale up through the access hole in the dropping chamber tripod while pulling the scale slightly towards yourself (the hole is located directly above fiber optic input on the interferometer base) until it contacts the top of the interferometer base. The upper reference height should be approximately 6 cm. Record this value in the system check log. The sum of the upper and lower reference heights (approximately 13 cm) will be entered as the reference height term in “g” Process | Setup| Information. See the g Software Manual for instructions**.**

3.1.6 Cable Connections

- If the computer is not mounted in the electronics rack, remove it from its shipping case and place on the top of the electronics case. Make sure the power switch is off.
- Connect the computer power cable to the power supply panel.
- Connect the PCMCIA cable from the "Magma" PCI unit to the laptop.
- Connect the BNC cable from the interferometer base "TTL" connector to the "CHAN A" connector on the computer time interval card.
- Connect the BNC cable from the "10 MHz" connector on the power supply to the "CLK" connector on the computer time interval card.
- Connect the BNC cable from the TRIG OUT connector on the SIM to the "EXT ARM" connector on the computer time interval card.
- For the WEO Model 100 laser:
    - Connect the BNC cable from the OUTPUT connector on the front panel of the laser controller to Channel 3 of the patch panel . Make sure the meter select switch on the laser controller is set to the "1F" position.
- For the Model ML-1 Laser:
    - Connect the LASER LOCK and LASER MODE cables from the ML-1 controller to the corresponding connections on the front of the SIM.
- Connect the BNC cable from the METER MONITOR connector on the ion pump power supply to "ION" on the SIM. Set the meter select switch to the 10-4 μA scale.
- Attach the rest of the system cables as described below. Both ends of all cables are labeled with the proper location for each connector.
    - Make sure the dropper controller is in RESET mode (press RESET on the SIM).
    - Connect the rotary shaft encoder cable (blue Lemo connector) from the power supply panel to the blue Lemo connector on the motor drive assembly.
    - Connect the DC motor power cable (orange Lemo connector) from the power supply panel to the orange Lemo connector on the motor drive assembly.
    - Connect the APD power cable (green Lemo connector) from the power supply panel to the interferometer base "power" connector.
    - Connect the ANALOG cable from the IB to the "ANALOG FRINGE" input on the rear of the SIM.

3.1.7 The Superspring

- For detailed instructions on operating the Superspring, please see the Superspring section of the SIM Manual.

3.1.8 Beam Verticality

- Loosen the lock on the side access door of the interferometer base (located directly below the beam block controls) and slide the door open.
- Remove the top cap of the alcohol container and place the container inside the interferometer base. By eye, center the alcohol pool left/right and slide it all the way back until it contacts the rear wall. This insures the laser spot is centered in the alcohol pool.
- Do not adjust the infinity focus of the collimating telescope! Adjust only the eyepiece.
- Pull out both beam blockers and align the test and reference beams by making the beams coincident in the telescope. Align the beams by adjusting the two screws on the fiber optic mounting plate (mirror mount) on the interferometer base only! Do not adjust the twiddler or the mirror below the telescope (mirror #2) when the alcohol pool is in the interferometer; only adjust the fiber optic mounting plate screws. Note that both beams move with respect to the telescope crosshairs as you adjust the mirror mount screws.
- Adjust the fiber optic plate mounting screws until the reference beam and alcohol spots are centered over each other (note that is not necessary to have the beams centered in the telescope field of view).
- If the alcohol spot is noticeably bigger or blurrier than the reference beam, this may be an indication that alcohol is dirty and needs to be replaced. We recommend flushing the pool a few times with alcohol before filling it. Fill it approximately half way.

3.1.9 Fringe Optimzation

- To optimize the fringe signal, the test and reference beams must be made perfectly coincident and parallel. The two interfering beams should be perfectly overlapped and also have no angular deviation for the greatest signal. The translation of the test beam relative to the reference beam is done by adjusting the translator plate (sometimes called twiddler). The angular deviation is minimized by adjusting mirror mount # 2, located below the telescope (see figure 2-8).
- For convenience, it is possible to move the test and reference beams to the center of the telescope viewfinder by adjusting mirror # 3, located in front of the telescope objective. Note this does not affect the interferometer alignment; it is only for the user’s convenience.
- Look in the fringe viewer and adjust the twiddler until the test and reference beams are coincident (overlapped).

- Look in the telescope and adjust mirror # 2 so the test and reference spots are overlapped. Use the two knobs that are diagonally opposite of each other. The two beams are now coincident and parallel.
- Connect the ANALOG output on the SIM to an oscilloscope, with the following settings:
  - Scale = 1 V/div
  - Sweep = 2 μsec/div
  - AC coupled input
- Make sure the laser is locked (either RED or BLUE). Set the dropper to OSC mode (See SIM Manual). This moves the cart slowly up and down at a constant velocity and produces a constant frequency fringe signal which is useful for adjusting mirror # 2.
- Maximize the fringe signal on the oscilloscope by adjusting mirror # 2.
- Maximize the fringe signal on the oscilloscope by adjusting the twiddler. Nominal fringe signal (peak-to-peak) is 1-2V. Note that amplitude of the signal is divided by 2 internally in the SIM – so a measured peak-to-peak voltage of 2 V at the SIM, will actually correspond to a true 4 V amplitude imeasured directly at the ANALOG output on the IB.
- Terminate OSC mode (see SIM Manual).

If the fringe amplitude is too small (less than 1V, or has dropped noticeably from earlier measurements), it is most likely a sensor unit alignment problem. If the legs that support the Upper Unit are not lowered perfectly vertically during setup, the Dropper can twist or tilt as the lower unit separates away from it. The first thing to do is to re-couple the units, carefully raise and then lower the Upper Unit legs, decouple, and re-measure the fringe amplitude. Also check that the top window of the Lower Unit has not become excessively dirty.

Laser power is also directly related to fringe amplitude, but it is very unlikely that the laser power will change drastically from measurement to measurement. Section 4.2 discusses adjustments of the laser power.

3.2 Software Set Up

Verify that AC Power is enabled, and then turn the PCI Unit (Magma) on.. Then turn the Computer on. The PC should always be powered up *after* the PCI Unit.

See the g User's Manual for a complete discussion of the software and setup procedures. Listed below are some FGL specific set up notes.

3.2.1 Information Setup

Reference Height- enter the total reference height.

3.2.2 System Setup

FGLs typically ship with "L Series" (Micro-g ML-1 lasers) and the laser frequencies are calibrated at Micro-g (see Section 2.4 for details on the ML-1 laser). It should not be necessary to change these values! Set the Pre-run lock time to be approximately 30-60 s. This is the time the laser is allowed to lock prior to the beginning of each set. In the *Acquisition* section it is necessary to make sure that there is enough time to take all the data and allow for laser lock between sets.

The correct Guide Card and A2D Card Parameters must be set in the same manner using the respective "Setup" buttons. Please refer to the instrument sheet specific to your instrument for the correct values.

3.2.3 Acquisition Setup

Next, select the appropriate start time option, and then enter the drop interval (a minimum of 1 second should be used with an FGL). The set interval should be set to your choosing. Finally, note the Pulse Delay is set automatically (though it can be entered directly by the user) – this is amount of time before the drop that the cart is lifted. In all cases, if the intervals are inconsistent the software will warn you.

Users often ask: "how much data is enough?" The short answer is to take enough data so that statistically you have the precision you desire. This might require a short test run to determine the drop-to-drop scatter in the measurements. Typically to get a good measurement at a location, it is desirable to run for at least 12 hours, or preferably 24 to cancel any uncertainties in the earth tide and ocean load corrections. 100 drops every 5-10 seconds over 24 sets is typical.

3.2.4 Control Setup

The first section in *Control Setup* is “General Terms” showing the gravity corrections that can be applied. For the initial setup, select all of these terms. “Tidal Terms” is next. Select “ETGTAB” for the first test run. For the laser section, select the Auto Peak Detect/Alternate to switch between Red and Blue (the software will then automatically select the mode and lock the laser prior to each set). For the “Data” section of this page enter the starting fringe and number of fringes to fit for each drop. These values, usually between A rejection sigma value must also be entered (nominally 3). A discussion of these corrections, including System Response can be found in the *g* manual.

3.3 Running the Gravimeter

3.3.1 Starting the Measurement

Before starting the meter, make sure of the following:

- Superspring and Dropper have been unlocked, the Superspring servo is on, and the units have bee separated.
- the dropper controller is set to the drop mode
- the dropping cart is at the bottom position.
- the laser is in REMOTE (or "COMPUTER") mode, (and should therefore be UNLOCKED at this point. Whether the mode is RED or BLUE at this point is irrelevant.) The software will automatically select the mode and lock the laser prior to measurement.
- the Rubidium LOCK LED is on

In *g,* Select *Process* | *Go,* or hit the GO button on the toolbar, or use F5 as a quick key

Assuming the meter is functioning correctly, the "State" display will show the value of gravity (among many other things), a graph of each drop relative to the current mean value, and the residuals of the parabola fit. See the *g* User's Manual for a complete discussion of all the *g* windows.

When the first set is completed, it is automatically saved to disk. At this point, if the application is stopped, the Project is no longer in real time mode. That is, if you enter *Stop* and then *Process* | *Go*, the program will replay the data, rather than operate the FGL.

When all the sets have finished, it is safe to quit the application (the data are already automatically saved). If you notice a problem, and stop the acquisition during the first set, you can restart the project without creating a new project. If you stop during any other set (after Set 1) however, *g* will automatically save all the completed sets and you will lose whatever data was in the incomplete set. **Note that it is important not to stop *g* until the data from the previous set(s) has been written to disk** (this can be seen on the bottom right of the screen). Stopping the program during this time can cause *g* to crash and data to be lost! This process can take several seconds.

3.3.2 Data Quality

While a complete discussion of data analysis and interpretation is beyond the scope of this manual, a basic understanding will help ensure that your data is of high quality.

- Drop Residuals. The residuals are the difference between the actual, measured fringe location and the final, best-fit parabola. Make sure that the residuals are relatively flat (<1 nm).
- The State Window
    - Note the Drop Gravity Value. Verify it is reasonable.
    - Note the values of the analog signals: For example, are the barometric pressure and spring position, reasonable and stable?
    - Note the value, in μGals, of the gravity corrections. Are they reasonable?
- Drop Gravity. Is the drop-to-drop scatter reasonable, given your location? In a quiet, stable, laboratory, this should be approximately 50-100 μGal. In the field, of course, this might be higher. Is the mean stable? That is, there should be no noticeable drift in the mean value throughout the set.
- Laser. Between sets, verify that the system is unlocking the laser, and then relocking to the alternate laser peak before the next set starts. From set-to-set, are the RED and BLUE gravity values self consistent? If for some reason the RED and BLUE locks have become switched in the software, a 1.4 milli-Gal difference will be observed. This can be easily fixed by stopping data collection and clicking the 'Switch' button found in the 'Setup' tab of the 'System' parameters. (This can be done in replay as well.)

3.3.3 Reprocessing Data

Once the measurement is finished (or if it is stopped after the completion of at least the first set), clicking *Process | Go* will cause the system to "replay" the data. The program will ask you if you would like to overwrite the previous output file (project.txt). Clicking YES (or choosing a different output filename), will cause the program to read the data files from the disk, and re-process each drop. If desired, it is possible to change the input parameters (common examples include a new nominal pressure, more detailed location values, etc.) and then replay the data. The parameter settings in place at the actual time of measurement can always be recovered by clicking *Edit | Reset | All*.

3.4 Packing the FGL

Note that even if the instrument is to be stored for a few months, it is best to leave it under vacuum with the ion pump ON. Only if shipping regulations require it, should the ion pump be turned off.

- Close all the windows on the computer, and power the computer down.
- Turn SERVO off and travel-lock the superspring (Lower Unit).
- RESET the dropping controller and enable the Travel-lock on the dropping chamber (Upper Unit)
- Turn DC and AC POWER off
- Make sure the ION POWER is on! (Unless shipping)
- Place dropper in its travel case.
- Remove the dropping chamber tripod, disassemble legs, and place in travel case.
- Verify laser is off, disconnect cables to laser head
- Place laser head and IB unit in travel case.
- Verify Superspring is travel-locked and place in travel case.
- Place Superspring tripod in travel case.
- Pack up all cables
- Pack up electronics case.
- Verify that ion pump has AC power (unless shipping).

4 SYSTEM ALIGNMENT AND OPTIMIZATION

4.1 *Setting the Laser Temperature*

It is quite important that the ML-1 laser temperature be constant. Please refer to the ML-1 User's Manual for information on temperature issues.

4.2 *Aligning Optical Fiber to Laser Light*

Aligning the fiber to the laser head correctly is extremely important: not only does a proper alignment insure the maximum interference fringe amplitude, it also governs the stability of the laser power. It is crucial that the fiber be aligned with the direction of the laser beam and also rotated about its axis so that its polarization matches that of the laser beam.

4.2.1 Optical Isolator

Between the laser head and the entrance to the fiber optic coupler (or "fiber"), the laser passes through an optical isolator. This component allows the laser light to travel through it, but does not allow (reflected) light to return back to the laser cell. This is important because any errant light entering the laser cell (referred to as "feedback") can interfere with the stability of the frequency lock.

The isolator is optimized at the factory to provide maximum feedback rejection and the user should not have to adjust it. However, if it is noticed that a piece of the isolator is loose, contact Micro-g immediately to receive information on reassembling the isolator (or receiving a replacement). If a piece is loose, it is extremely likely that isolator is no longer functioning and that the laser will not lock reliably.

The only adjustment necessary regarding the isolator is this: the whole unit must be rotated so that its polarization matches that of the laser. Simply place a power meter at the output of the isolator and rotate the isolator until the power is maximized. Clamp the isolator in place.

4.2.2 5-Axis Mount

The fiber is coupled to the laser head via a "5-axis" mount. The name refers to the fact that the mount allows lateral translation of the fiber relative to the beam in both the X and Y directions (2 axes), the mount allows tilt of the fiber in both pitch and yaw (2 axes), and the mount allows longitudinal translation of the fiber so as to focus the laser beam into the fiber (1 axis). Note the mount also allows rotation of the fiber relative to the beam (yet one more axis for an actual total of "6")---the subject of the next section.

Getting laser light through a fiber is somewhat tricky and requires patience and practice. However, the principles are quite simple: one is trying to align the entrance of the fiber with a laser beam focused down to a few microns in diameter. Both the location of the fiber entrance and the fiber's angle must coincide with that of the laser beam.

- Attach the 5-axis mount to the laser head and translate it such that the laser light is traveling through the center. (Verify by holding a piece of paper up and making sure the beam is not clipped)
- Attach the fiber to the 5-axis mount and tighten firmly.
- Use the X and Y screws on the side of the 5-axis mount to get some light through the fiber. While you should never look directly into the fiber, it should be possible to see the output end of the fiber "glow" with a small amount of light. If no light is visible, slowly translate the X and Y screws in a search pattern while looking for a "glow" at the output end of the fiber. When a small glow is visible, it is now best to attach the fiber to a laser power meter.
- Using the power meter, carefully adjust the X and Y screws until the power is maximized.
- Now use the three screws on the front to adjust the angle of the fiber. Iterate through all three screws – this not only changes the angle, but the focus (distance from the fiber entrance to the focusing lens) as well---turning each one in the direction of maximum power.
- Now return to the X and Y screws and adjust them *slightly* to maximize the power. Then return to the three front screws and repeat the procedure.
- After many (10 or more) iterations the laser power should be maximized.

4.2.3 Fiber polarization

When the power is maximized (or at least about 100 μW for an ML-1 laser) it is then necessary to rotate the fiber so as to match its polarization to that of the laser. Note that, unfortunately, this most likely means a great (if not complete) loss of light in the fiber! Finally, note that this procedure requires not only a sensitive laser power meter, but a high quality, rotatable, polarizer as well.

- Shine the light from the output of the fiber through the polarizer and onto the laser power meter. Rotate the polarizer until the laser power is maximized and note the value. This is the "transmitted" power.
- Now rotate the polarizer until the power is minimized (this might require a rescaling of the power meter). Next, form a coil of excess fiber in your hand and let the heat slightly change the length of the fiber. This will most likely cause the power to increase. Note the maximum value attained. This is the "rejected" power.
- Calculate the ratio of "rejected" to "transmitted". This ratio should be less than 1:100.
  - If the rejection ratio is ≤1:100 then great! Make sure the "large" black screws on the front of the 5-axis mount are tight, fine tune the laser power, and proceed to the *Last Step*.

  - If the rejection is ≥ 1:100. Note the orientation of the fiber relative to the 5-axis mount. Slightly loosen (so as not to drastically change the angle of the fiber) the 3 "large" black screws on the front of the mount, slowly rotate the whole fiber. There are two optimal orientations of the fiber, 180° apart. If the rejection was close to 1:100, rotate a few degrees. If the rejection was basically 1:1, then rotate approximately 90°. If the rejection was in between, use the above information to estimate a reasonable amount of rotation.
  - Once the orientation has been chosen, use the 5 adjustment screws to get at least 100 μW of light through the fiber again. Repeat the rejection measurement and calculation.
  - Repeat the whole procedure (rotate, regain the light, measure the rejection) until the rejection is at least 1:100. Once 1:100 is achieved, use the 3 "large" black screws to clamp the fiber rotation into place and proceed to the *Last Step*.
- *Last Step!*
- Now that there is laser light through the fiber and the rejection is better than 1:100, we must finally optimize the laser power. As above, use all 5 screws to maximize the power.

- Next, carefully loosen the translation screws that attach the 5-axis mount to the laser head. Loosen as little as possible so that the angle is not significantly changed and yet the 5-axis mount can still translate. While monitoring the output power, move the whole 5-axis mount relative to the laser beam until the power is maximized. It is often possible to get an additional 15 μW of power using this "trick". When the power is maximized, tighten the 5-axis mount back in place and fine tune with the 5 adjustment screws, if necessary.
- Goals:
  - The isolator will transmit roughly 60% of the laser power
  - The fiber will transmit roughly 60-70% of the power

With an ML-1laser producing about 1.2 mW, it should be possible to achieve 400 μW of power at the output end of the fiber.

5 VACUUM CHAMBER: Turbo Pump and Baking Out

Under normal operations, the vacuum in the FGL dropping chamber is maintained by an ion pump. Any residual molecules in the chamber that enter the ion pump are ionized by the 4 kV potential and plated out. This procedure only works at high vacuum levels as the current drawn by the ion pump is directly proportional to the number of ionizations per second. If the vacuum has been degraded (the ion pump has been off for more than a few hours), it will be necessary to use the turbo pump to "regain" the vacuum. If the vacuum is very poor (ion pump off for many weeks, or the chamber has been opened to atmosphere), it will be necessary to bake (heat) the chamber while turbo pumping.

5.1 Setting up the Turbo Pump

Remove the turbo pump from its case and place it near the dropping chamber vacuum flange. Connect the turbo pump to the dropping chamber using the flexible vacuum hose which has a vacuum flange on both ends. The vacuum hose is normally stored in the turbo pump case underneath the turbo pump. Make sure not to stress the bellow tube. See Figure 13.

Figure 13. Turbo pump connected to dropping chamber. Note the minimum stress in the hose.

Attach the vacuum hose to the turbo pump. The quick flange has a clamp which mates the two vacuum flanges with an o-ring seal. It is important to keep the o-ring seal and vacuum flanges free of dirt or scratches to avoid leaks.

The bellows valve is located above where the vacuum hose connects to the dropping chamber. There are two different circumstances which dictate whether the bellows valve is to be open or shut when starting the turbo pump:

- The dropping chamber is under (partial) vacuum. If the chamber is under partial vacuum, the vacuum valve should remain closed. Do not open the valve until the turbo pump has evacuated the air inside the flexible hose and come to full speed. (Otherwise air in the hose can be sucked into the chamber.) Once the turbo pump has reached a normal speed and normal operating pressure, slowly open the valve. It is important to open this valve slowly because if there is actually air in the chamber, a large amount of air can damage the turbo pump. Slowly turn the valve until it is completely open, all the while making sure that the turbo pump is still at full speed.
- The dropping chamber is at atmospheric pressure. If the dropping chamber has been open to air, the vacuum valve must be opened before starting the turbo pump. This is important because the turbo-pump can be damaged if it is suddenly exposed to air when operating at its normal pumping speed. In this case, you are evacuating the chamber and the vacuum hose at the same time. The dropping chamber will also require a baking-out procedure to remove water vapor from the system.

After the correct position for the vacuum valve on the dropping chamber has been determined, plug the turbo pump into the proper AC power. Make sure the small relief valve on the turbo pump vacuum flange is closed. Turn the switch on. The pump will start immediately and slowly increase its speed. When the turbo-pump reaches its nominal operating speed (usually about 70-75 krpm), The small green LED on the side of the turbo pump will blink until the turbine has come to full speed, at which point the LED will be lit continuously.

Ideally, while pumping down the system, the AC power will not be interrupted. However, if the power is interrupted, the system will not actually vent to atmospheric pressure.

5.2 Baking Out the Dropping Chamber

When the dropping chamber has been exposed to air or when the ion pump has been off for more than one month, it should be baked out while the turbo pump is operating.

Bake-out involves heating the dropping chamber and ion pump to “evaporate” water and other heavy molecules from the interior surfaces while the system is being turbo-pumped. This decreases the pumping time by speeding the out-gassing processes within the chamber. In cases where the ion pump has been off for several weeks, it may be helpful to bake out the chamber even though it has not been opened.

5.2.1 Heating the Chamber

The magnets on the ion pump can be damaged by high temperatures and should be removed prior to baking out the Dropping Chamber. The is done by disconnecting the high voltage BNC to the Ion Pump (make sure ION POWER is off!), and then removing the small screws that hold the cover in place. Once the cover have been removed, locate and remove the small screws that hold the magnets in place, and then carefully slide the magnets off of the ion pump.

To heat the chamber, first make sure the travel lock is engaged (this allows thermal contact between the test mass and the chamber). Wrap the heat tape around the chamber being careful to avoid double-wrapping the tape or touching bubble levels.

Turn on the power to the heat tape, and use a temperature probe (many multimeters have thermocouple probes) located directly between the chamber and the heat tape (the hottest location). It will take about 15-30 minutes to reach thermal equilibrium, but it is necessary that the chamber stabilize at approximately 60-70 ºC. **However, the temperature of the chamber should never exceed 80ºC as this can damage the ferrofluidic feedthrough.**

With the turbo pump on and evacuating the chamber, leave the heat on for 4-8 hours. Then turn the heat off, but leave the turbo pump on, letting the chamber cool for approximately 12 hours. A routine that works well is to start the chamber heat in the morning, monitor it throughout the day, turn the heat off at the end of the day, and let the turbo run (and the chamber cool) throughout the night. It should be ready for the ion pump the next day.

5.3 Starting the Ion Pump

At this point, the system should be at room temperature. The dropping chamber should be under vacuum, the turbo pump should be operating at normal speed, and the ION POWER should be turned off at the main control panel. The next step is to migrate the system to the ion pump so that the turbo pump can be removed from the system.

Use a voltmeter(s) to monitor both ION CURR and ION VOLTS on the main control panel. Leave the turbo pump running and connected to the dropping chamber. Turn on ION POWER, and check that ION VOLTS is increasing to approximately 4 kV within five minutes after turning on the ion pump. If the ion pump voltage has not reached the operating voltage within five minutes, turn off the power and continue pumping with the turbo pump for at least one hour before trying the ion pump again. Leaving the ion pump on with low voltage and excessive current significantly shortens the lifetime of the pump. Once the ion pump has reached its operating voltage, monitor ION CURR. This value should be slowly falling (to a value less than 0.1 volts) as the ion pump ionizes less and less molecules (drawing less and less current). This means the ion pump is operating normally (though the turbo pump is still helping at this point).

Once the ion pump has started, close the vacuum valve fully. It is normal for the current to increase after the valve is closed, but after a few minutes it should begin decreasing again as the ion pump continues to pump. After the current has begun to decrease reliably, the turbo pump can be turned off. After the turbo pump has come to a stop, use the relief valve on the turbo pump to re-fill the vacuum hose with air (and then close the valve so as to be ready for a future pump-down). Remove the hose from the chamber and turbo pump. Replace the blank flanges on the vacuum valve and turbo pump intake and remove the bellows tube. Replace the turbo pump in the shipping case; it will no longer be needed for operation.

6 System Specifications

6.1 *Power*

- 100-240 V AC, 50/60 – Average Consumption: 150 W

6.2 *Operating Temperature*

- 18ºC – 30ºC laboratory temperature

☐ Quick Set-up/Take-down

☐ *Setup*

☐ Check that ion pump is powered on and operating correctly
☐ Connect electronics to local power
☐ Remove laser head from case and connect to electronics
☐ AC Power ON
☐ Laser power ON (laser in “warm up” mode)
☐ Place and level Superspring tripod at measurement location. Measure “reference height”
☐ Place Superspring on tripod – travel lock towards bull’s eye
☐ Place IB on top of Superspring – laser toward bull’s eye
☐ Assemble Dropping Chamber Tripod and place on IB – measurement hold towards bull’s eye
☐ Place Dropping chamber in tripod.
☐ Connect Cables to Superspring, IB, and dropper.
☐ Unlock the Superspring
☐ Use Dropping Chamber tripod feet to decouple from IB.
☐ Unlock dropper
☐ DC Power ON
☐ Lock laser temporarily and check fringes (OSC mode). Return laser to WARMUP mode (lock off)
☐ “Zero” the spring, let it settle, and then turn SERVO ON
☐ Connect computer and patch panel cables
☐ Turn computer power ON and set up software
☐ Enter the tripod “reference height”
☐ Calculate set sizes and duration (drop interval to 1 second minimum)
☐ Set laser control to REMOTE
☐ Verify spring position, temperature settings, etc.
☐ Set dropper controller to drop mode (INIT)
☐ Take data

Tear Down

☐ Set dropper controller to RESET
☐ Superspring servo OFF
☐ Travel lock Superspring
☐ Travel lock Dropper
☐ Laser power OFF
☐ Back up data (if applicable) and turn computer power OFF
☐ Main power (DC & AC) OFF
☐ Disconnect all cables (but get power to ion pump!)
☐ Pack everything into cases