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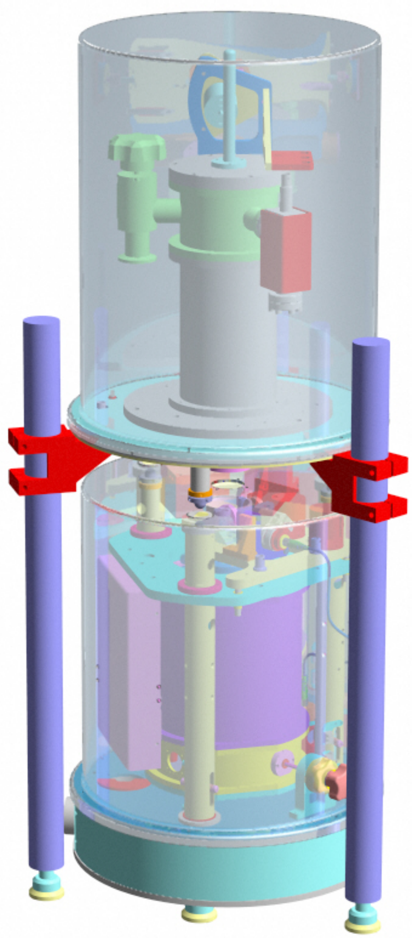
A-10 Portable Gravimeter User's Manual



JULY 2008

TABLE OF CONTENTS

Table of Figures

1 INTRODUCTION

1.1 The A-10 Absolute Gravimeter

The A-10 absolute gravimeter is a high precision, high accuracy, transportable, field ready instrument that measures the vertical acceleration of gravity (g). While the A-10 will operate as a reliable and accurate laboratory instrument, it is designed primarily with field operation in mind: it operates on a 12V DC (i.e. vehicle battery) power supply, and is optimized to facilitate fast field operation: depending on site conditions, it is possible to acquire over 20 absolute field stations in a single day!

The operation of the A-10 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 A-10 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 A-10 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 A-10 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 A-10 inherits the stability of the length and time standards as the basis for its absolute gravity determinations.

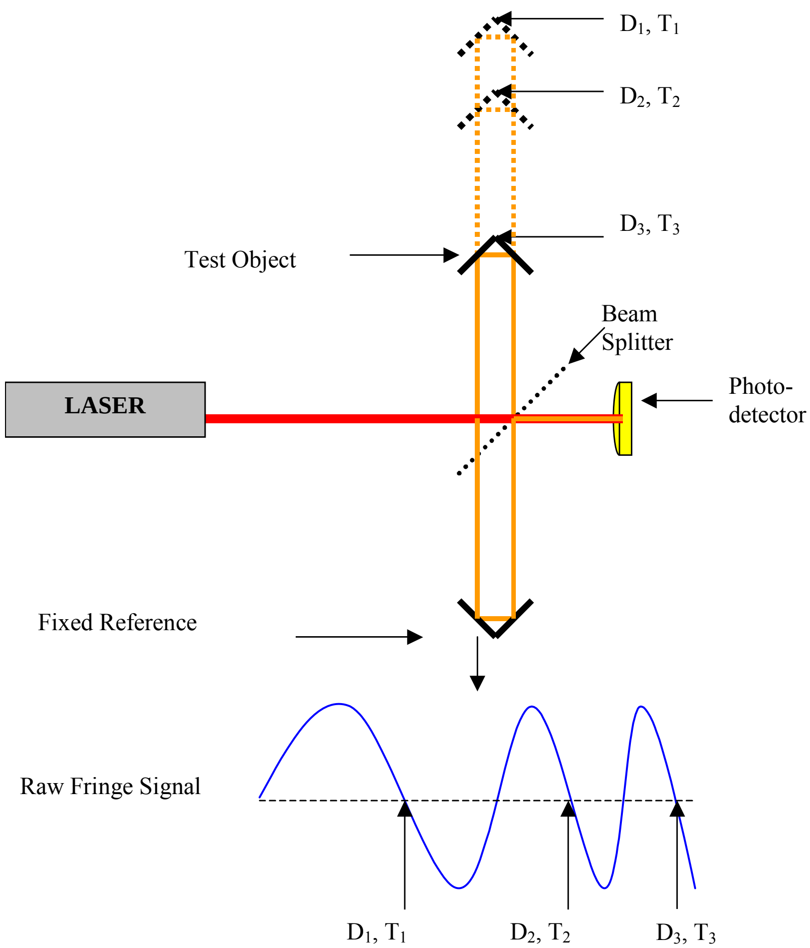


Figure 1 Direct Measurement of Absolute g

Figure 1 shows how gravity is measured with an A-10. 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 A-10 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 A-10 on massive bedrock will usually provide the best results. The A-10 is equipped with a tripod to adapt to rough surfaces that are frequently encountered in the field (up to 10º slope and 2 cm of roughness). It is important to keep the A-10 out of direct sunlight and shielded from wind and precipitation. Excessive, sudden temperature changes should be avoided.

1.5 Major Components of A-10

Figure 2 shows the fully assembled A-10. Major components include

- Dropper Unit (dropping chamber, temperature control)

- Interferometer Base or "IB" (laser, spring, interferometer, leveling, temperature control)
- Computer (lunch box type)
- Cables
- Shipping/Deployment Cases
- System Electronics (See Figure 4 and Figure 5)
- Verticality Checker ("Beam Checker")
- Terrain Tray (tripod)
- Turbo Pump
- 12 VDC, deep cycle, battery
- Battery charger

Optional Components:

- Laboratory (100-240 VAC) power supply
- Wind & precipitation shelter (tent)
- Wind & sun shelter (shade box)
- Insulating jackets
- Laser power meter
- Field oscilloscope

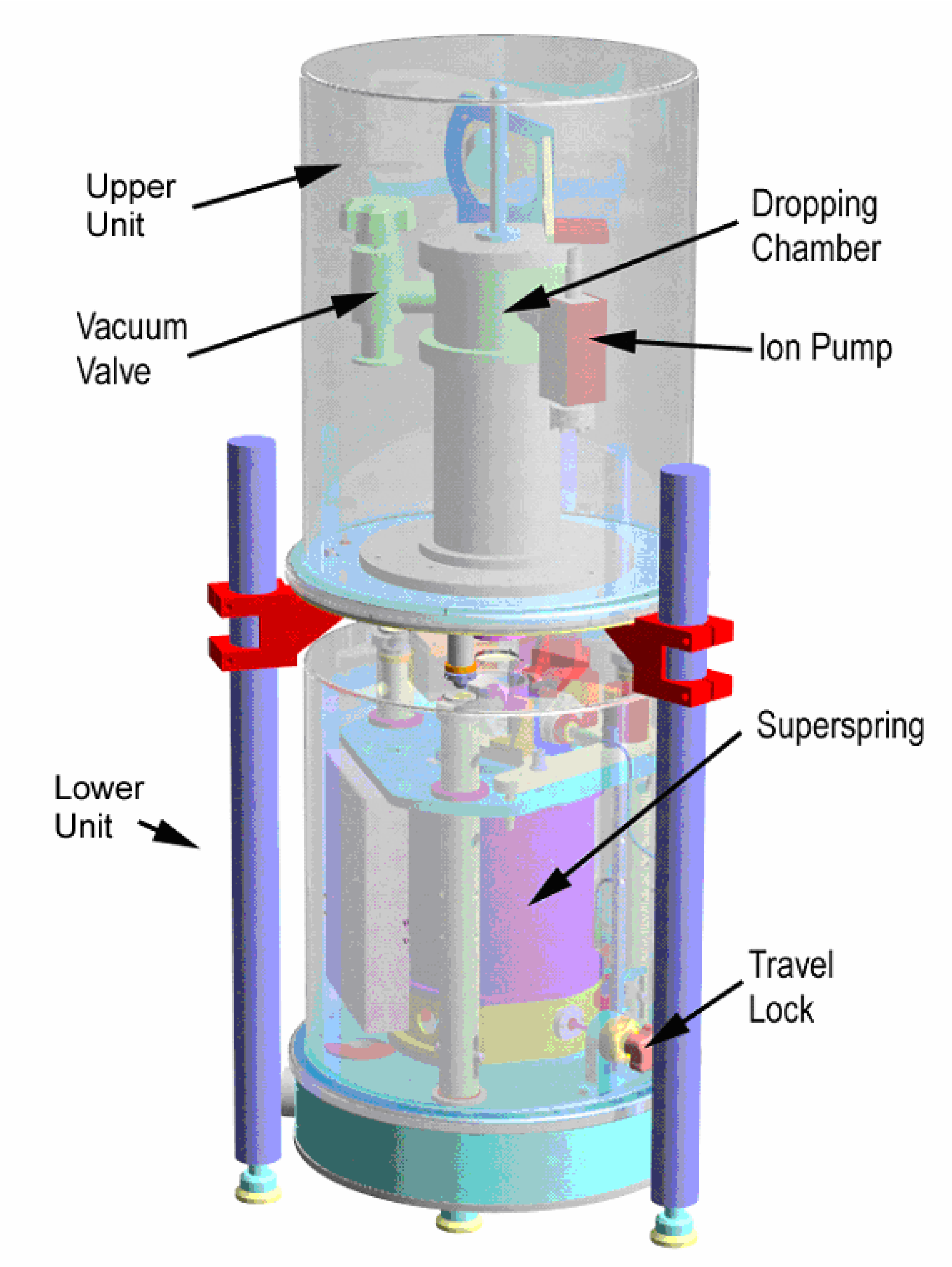


Figure 2. A-10 Schematic

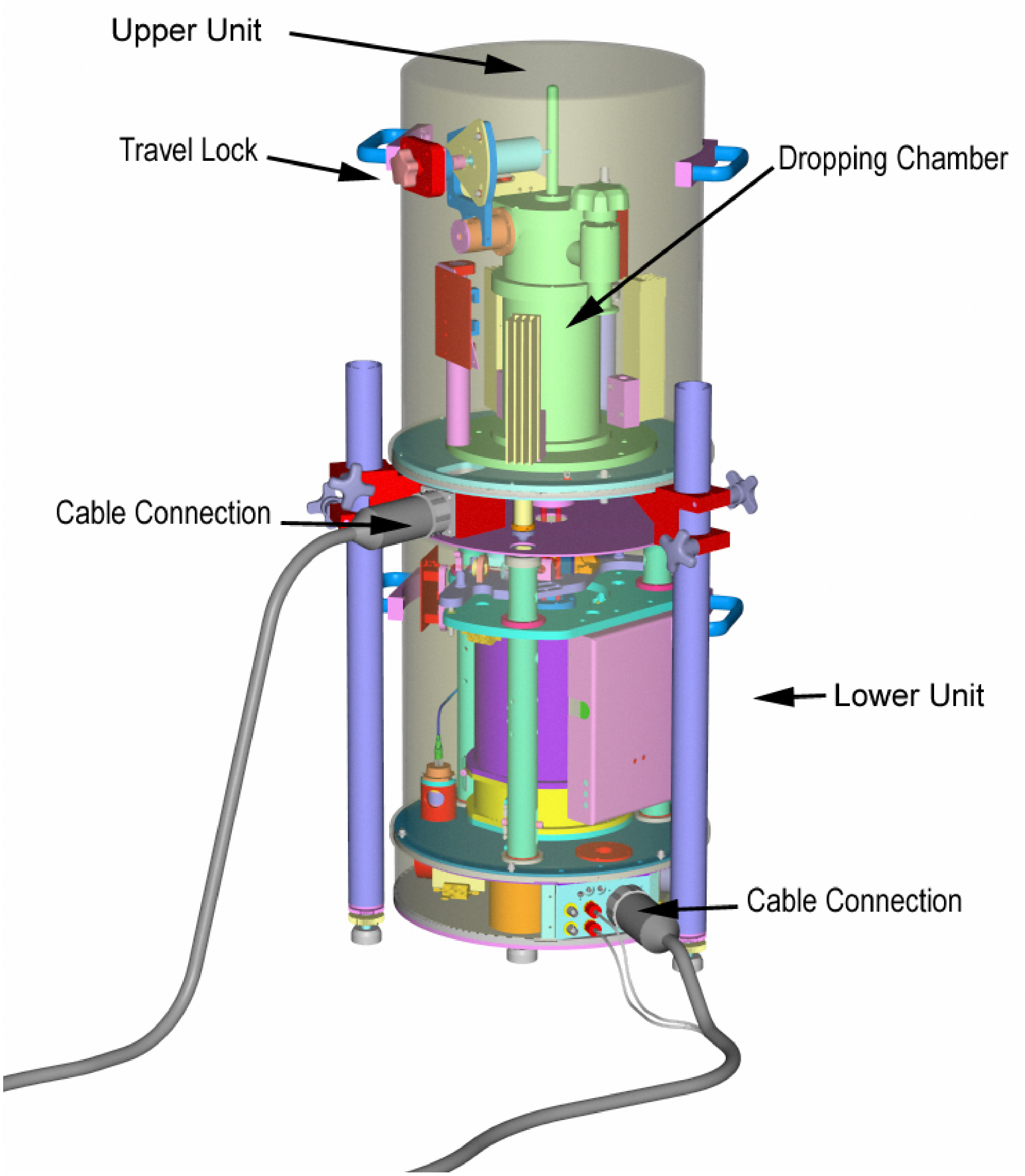


Figure 3. A-10 with cables attached.

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

Figure 5. 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.

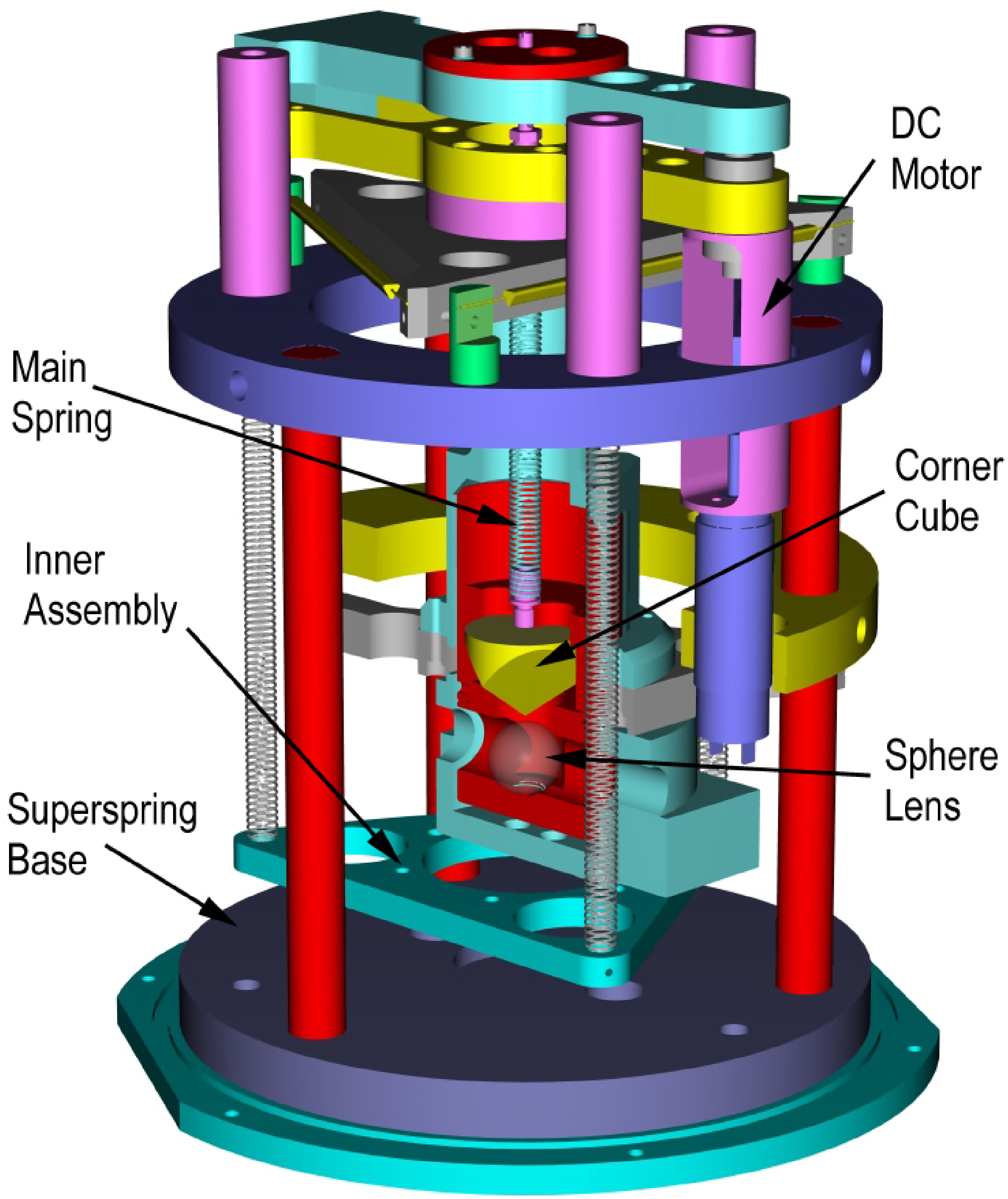


Figure 6. Superspring Schematic

The superspring is a double-stage spring system. A schematic is shown in Figure 6. 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. The servo circuit is activated by turning SS SERVO on with the A-10 controller. Note that if SS 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). This motor is activated by turning SS ZERO ON with the A-10 controller. By monitoring the SS POS connector with a voltmeter, one can see the position approach 0 V. 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. Finally, though it will not cause permanent damage to the system it is best to not zero the Superspring with the servo activated.

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 7 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.

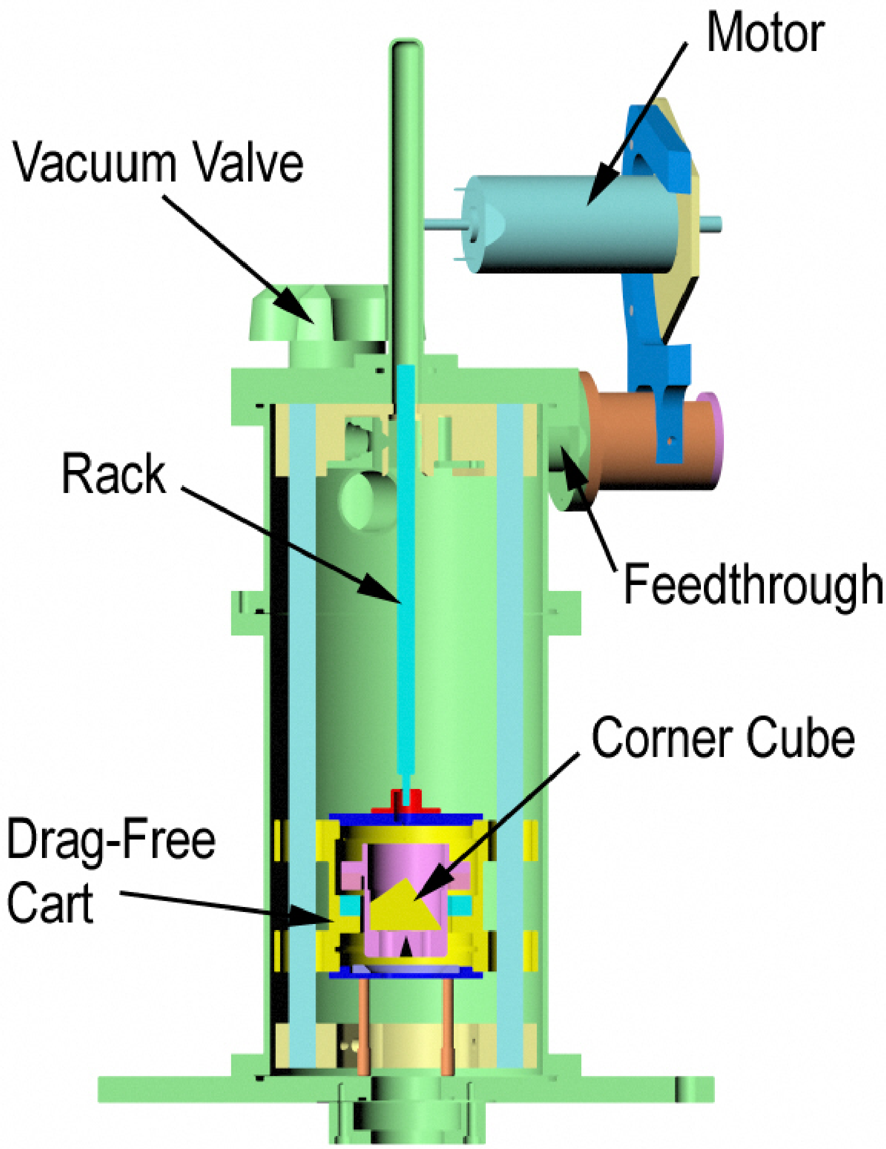


Figure 7. Dropping Chamber Schematic

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 uses three modes to operate the dropping chamber. These modes are OSC, DROP, and THROW (note however, that at the time of writing this manual, THROW mode is not yet supported). The operator also controls the status of these modes and the dropper triggering with the RESET/INIT switch and the TRIGGER switch.

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, press RESET/INIT until the STANDBY light is off, 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. If a TTL pulse is entered into EXT TRIG this will also cause a lift, and a separate pulse will cause the drop. These are normally supplied by the computer during data acquisition. To stop DROP mode, press RESET/INIT so that the STANDBY light is on. 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. Place the controller in OSC mode, and press RESET/INIT. 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 button at any time. The cart will automatically stop at the bottom of the next oscillation cycle. Take care not to hit the RESET/INIT button directly, as this will drop the test mass and cause excessive wear on the 'balls' and 'vees'.

2.3 Interferometer Theory

The A-10 interferometer is located in the upper portion of the lower unit, between the Superspring and the dropping chamber. Figure 8 shows a schematic. The function of the interferometer is to split the laser beam into the test and reference beams, and then recombine the two beams to cause interference on an optical detector.

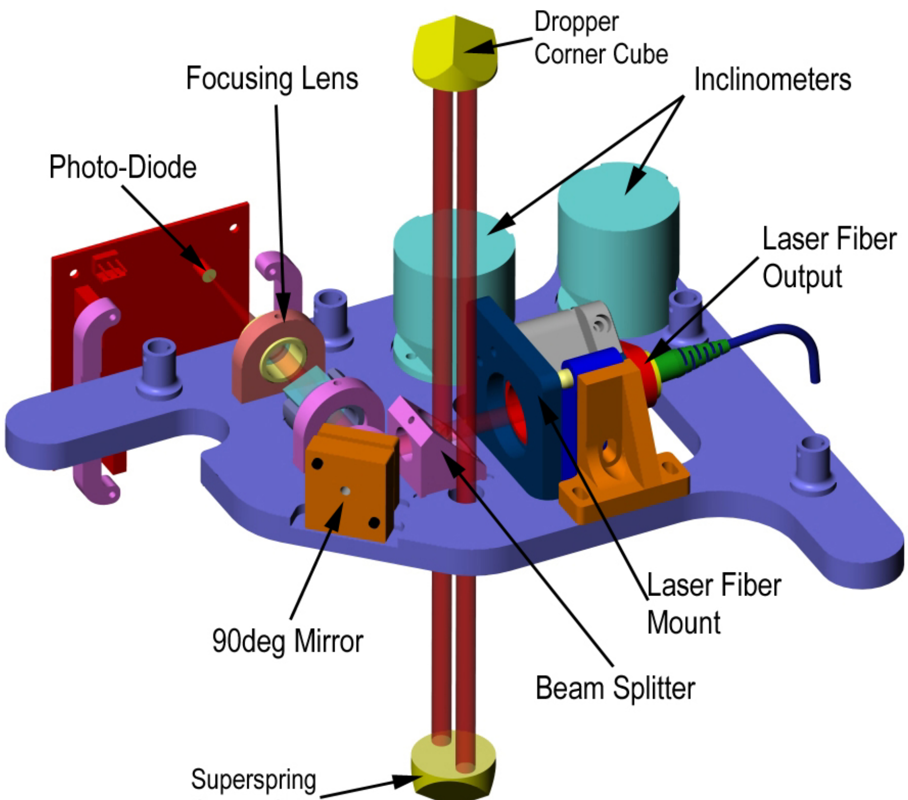


Figure 8. Interferometer Schematic. The laser light enters via the fiber, is split at the beam splitter (test beam is shown bouncing off upper and lower

corner cubes). The recombined beams are deflected 90º and focused onto the photo-detector.

The laser light enters the interferometer at the output of a polarized optical fiber. (Note that the input end of the fiber has been aligned at the factory so that its inherent polarization matches that of the output of the laser. See Section 5.2.3 for details. This adjustment is difficult and is only performed in rare situations.) The fiber output is held by a standard optical mount that allows the angle of the laser light to be adjusted relative to the interferometer. The laser light is split into two beams by a beam-splitting cube. The output end of the fiber has been rotated at the factory so that approximately 60% of the light is transmitted up into the dropping chamber, and 40% is transmitted through to the photo-detector. After the splitting cube, the beams are recombined. These overlapped beams then reflect off a mirror used to steer them to the photo-detector. The detector produces a voltage proportional to the intensity of the light, and a discriminator is used to produce logic (Transistor, Transistor, Logic, or TTL) pulses at the zero-crossing of each fringe.

2.4 Laser Theory

The A-10 employs a Micro-g Solutions Inc. model ML-1 HeNe, polarization-stabilized laser. Its 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 denoted in Figure 10 as red and blue. Note that red and blue are arbitrary choices and do not denote differences in wavelength.

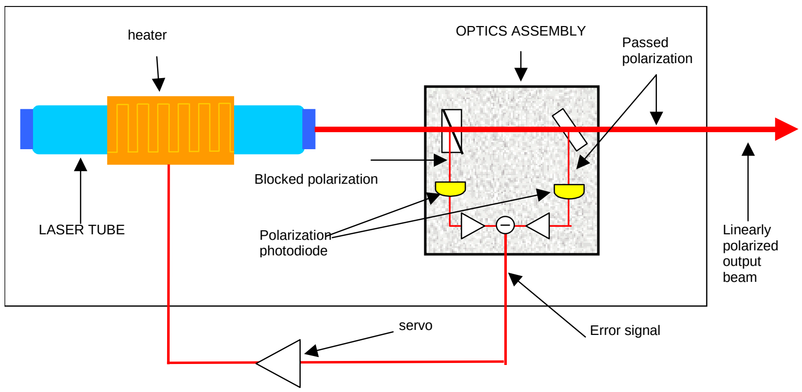


Figure 9. ML-1 Schematic. The intensity of two polarizations is monitored and fed-back to a heater that determines the cavity length.

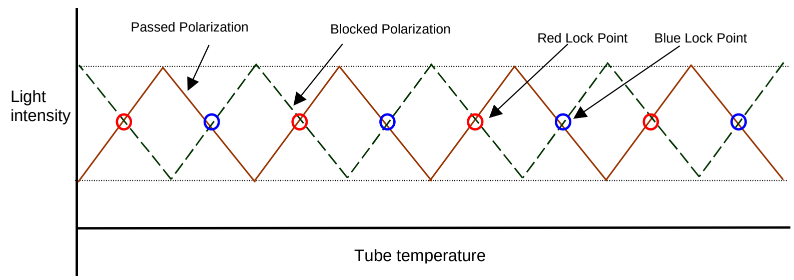


Figure 10. Intensity of the two polarizations as a function of temperature.

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 LASER CTRL set to MANUAL the laser is locked by turning LASER LOCK on. 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 LASER CTRL set to REMOTE (the left LED), 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 (monitored by LASER TEMP on the A-10 control panel).

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 5.2.3 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 A-10 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 A-10 SETUP

3.1 *Instrument Assembly*

The instructions below refer to two units: the Upper Unit (Dropper) houses the dropping chamber and the Lower Unit (Interferometer Base, or IB) consists of the laser, interferometer, Superspring, and leveling unit.

These instructions assume that the dropping chamber is already at a high vacuum level. See Section 6 for instructions on pumping out the dropping chamber. It also assumes that the operating temperatures of the dropper, interferometer, and laser have all been set. See Section 5.1 for temperature setting instructions.

Finally note that in references to the control buttons below, the user must operate the **button** on the control panel, not the LED indicating the button has been activated (or deactivated).

3.1.1 Pre-Operation Warm-up

(If the ion pump has been powered by an external source, disconnect it now. See Section 6.3 for ion pump details.)

The first step in setting up the A-10 is to connect the battery to the rear of the controller electronics. The battery leads are color-coded (black is ground and red is +12V DC). See Section 4.2 for power considerations. Next,

- To protect from static charge build up on the cable shields, it is safest to use a conductor (e.g. a ball of aluminum foil) to short out the pins on each end of the cables.
- With the power to the electronics still complete OFF, connect the two large cables from the electronics rack to the two sensor head units. Connect the electronics end first, then the sensor ends.
- Turn ION POWER is on. Then engage the CONTROL ENABLE switch and turn on the MAIN POWER.
- Enable Temperature control for Dropper and I.B. This turns on the heaters that bring the A-10 to operating temperature. Ideally the Superspring will come to thermal equilibrium before taking data. This can take easily take at least 4 hours – in general, it is best to power up the heaters the day before data acquisition is planned.
- Turn on LASER POWER. Also make sure that LASER CONTROL is set to MANUAL and LASER LOCK is off. Depending on the ambient temperature, the laser will come to thermal equilibrium in about one hour.

Again, if possible, it is best to power on the laser a day before acquisition is planned.

- Turn on RUB power. This turns on the Rubidium atomic clock. It takes approximately 5-10 minutes for the clock to become stable, at which point the LOCK light will turn on.

The appropriate warm-up time will of course depend on initial temperatures, and there are no hard and fast rules. A minimum of 1 hour of warm-up time is necessary, and at least four hours is considered ideal. A rule of thumb is "if you plan to measure gravity with the A-10 tomorrow, power it up tonight". That is, 12 hours of warm-up time ensures a stable system during measurement.

It is also important to ensure that the vehicle battery is charged. The A-10 is capable of pulling up to 25A from a 12V source. Average power consumption during full operation is about 16A. If operating from a vehicle, run the engine as needed to maintain the charge in the battery. See Section 4.2.3 for power and battery considerations.

3.1.2 Electronics System

The A-10 Electronics System is composed of an electronics rack (3 components) and a lunch-box type computer. The electronics rack is composed of the power supply/main controller, the dropper controller unit, and the input/output unit (patch panel). See Section 7 for detailed list of electronics connections. At this point, all electronic connections should be in place.

3.1.3 Setting up the Lower Unit

Remove the Lower Unit (Interferometer Base, or IB) from its box in the vehicle. Set it over the mark or point to be measured.

If the terrain is rough, or slopes at an extreme angle, it is possible to use the terrain tripod. In this case, place the tripod over the point to be measured, and adjust the leg length(s) until the bull's-eye level is centered. Using the height tool, measure the distance from the top of the tripod down to the reference mark. Add the built in height of the tripod (2.95cm) to the measured height, and enter this total height into the software under Setup | Information | Ref. Height. (If the tripod is not needed, enter 0 in the Ref. Height field. Place the Lower Unit on the tripod, taking care that the legs of the IB are centered on the tripod and that the unit is stable.

To level the unit, press the AUTO LEVEL button (the LED will light at this point). The leveling process can take anywhere from 5 – 45 seconds depending on the initial tilt of the Interferometer Base. Do not turn the auto-level function off at this point. Using the beam checker, as described in section 5.3, verify laser verticality.

3.1.4 Setting the Upper Unit (Dropping Chamber)

Remove the Beam Cover (rubber stopper or plastic cap) from the top of the Lower Unit, and be careful not to look directly into the laser beam (laser power is approximately 200 μWatts).

Place the Upper Unit on top of the Lower Unit allowing the feet to fit neatly into the three wells on the top of Lower Unit. Use the alignment markers to orient the upper unit. As a check, the control cables for both units should be between the same Upper Unit legs. The tripod legs for the Upper Unit may also require separate platforms underneath each foot if measurements are being taken on rough terrain.

Disengage the travel lock on the Dropping Unit, making sure the locking knob "pops out" about 5mm.

At this point the two units are in direct contact with one another. Make sure that AUTO LEVEL is still on, and manually lower the Upper Unit feet until they contact the ground and tighten the leg clamps. Take care that the legs are dropped as vertically as possible (it is usually best to tighten the clamps until the legs are just barely able to slide, drop the legs to the ground, and then fully tighten).

Next, locate the toggle switch near the base of the Lower Unit and flip the switch to the down position (See Figure 11). This causes Lower Unit to drop away from the Upper Unit, physically separating them. This separation eliminates the transfer of vibrations from the dropper to the inertial reference of the Superspring, and is crucial for proper operation. When the separation has completed, leave the switch in this position (do not toggle it back). Note that the switch has a neutral center position; this is not used in normal A-10 operations.

Slowly disengage the travel lock on the Superspring (turning gently to the "unlocked" position helps reduce the initial free vibrations of the Superspring).

Turn AUTO LEVEL off

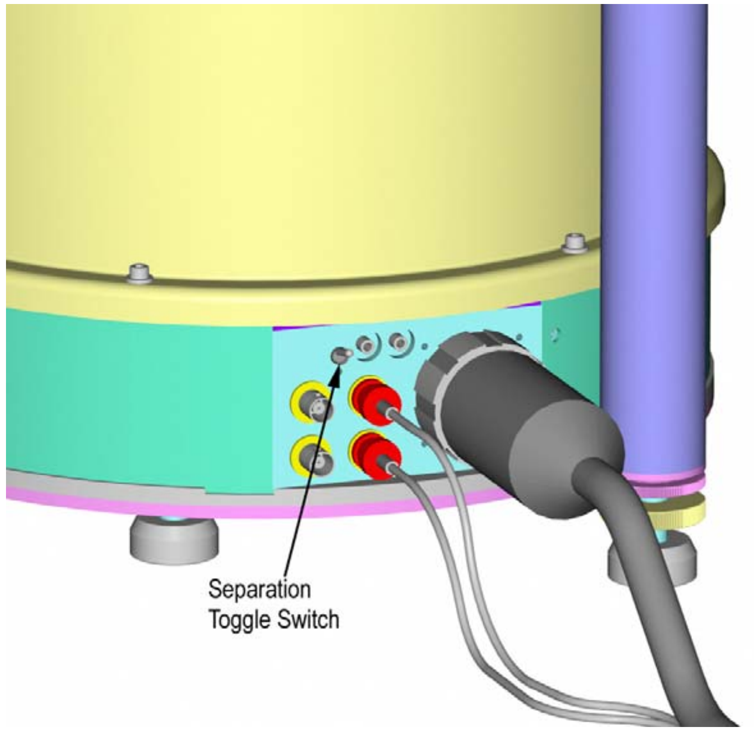


Figure 11. Separation switch used to raise (couple) and lower (decouple) Units I and II.

3.1.5 Dropping Chamber Controller Set Up

The Dropping Chamber Controller electronics provides a means to control the cart inside the dropping chamber. Before operating the dropper controller, make sure the Dropping Chamber travel lock is disengaged. There are several modes of operation but only two of these should be used in normal operation: OSC and DROP mode. OSC mode is used to move the cart smoothly upwards and downwards at a constant velocity to determine the size of the fringe signal from the interferometer (see Section 3.1.6 for fringe amplitude determination). This mode is convenient when aligning the interferometer because it provides a nearly constant, low-frequency fringe signal. OSC mode is used only during initial setup to verify that the optical system is operating properly.

DROP mode is used to make repeated drops of the cart during the gravity measurement. In DROP mode the computer can repeatedly initialize "drops" in which the cart rises to a pre-specified height and then drops suddenly so that the internal test object is allowed to freefall while the gravity measurement is taken.

Before changing modes, first put the controller into RESET mode by pressing the RESET/INIT button. In RESET mode the motor is disabled. Then select the appropriate MODE: OSC or DROP with the rotary knob and then push the INIT button to initialize the mode. The RESET/INIT light will turn off, and the chosen mode light will switch ON. Once the initialize button is pushed the controller will ignore any changes in the MODE switch. IMPORTANT: Before initializing a different mode first push the RESET button.

In OSC mode the cart will simply rise up and down at a constant velocity. When finished with OSC mode, simply press the TRIGGER button at any time. OSC mode will stop at the bottom of the next cycle. It is important not to push the RESET/INIT button to quit OSC mode, as the cart and test mass will crash down to the bottom of the drop and cause excessive wear on the system. Always press TRIGGER to quit OSC mode.

In the DROP mode the cart will perform repeated drops either from the front panel BNC external trigger (signal from the computer) or whenever the TRIGGER button is pressed. This mode must be initialized by pressing INIT until the RESET light of OFF. The dropper must be initialized and in the lower position before starting data acquisition.

3.1.6 Fringe Amplitude Check

A "fringe" refers to the interference between the test and reference beams in the interferometer. The amplitude of the fringe signal depends on many things, including laser power, and most importantly, system alignment. The A-10 is aligned at the factory and should provide optimal fringe amplitude if the A-10 is set up correctly.

To measure the fringe amplitude, attach an oscilloscope to the ANALOG FRINGE BNC on the system controller (Oscilloscope set up: 1V/div vertically and about 5µs/div horizontally, AC coupling). Using the dropper controller, place the dropper in OSC mode. Also, place the laser in MANUAL mode, and LOCK the laser (the RED/BLUE mode is not important).

You should observe a normal fringe signal amplitude of about 2-4 V (though it is possible to take data down to a fringe amplitude of about 2 V). Newer A10s split the analog signal into two paths: one to the Analog Fringe output on the system controller, and the other to the rear of the dropper controller. This means that ½ the signal is measured at the output. In this case, the "normal" fringe amplitude should be measured as approximately 1 – 2V peak-peak.

If the fringe amplitude is too small (less than 2 V, 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 5.2 discusses adjustments of the laser power.

3.1.7 Setting up the Superspring

(At this point, verify that the system has been leveled, and the Superspring has been un-travel locked)

Use a voltmeter to monitor the spring position (SS POS), and wait for the spring to settle down so that the "scatter" is about 50mV or less.

Next determine the spring position. After the spring has settled, determine its approximate mean position. If it is farther than 20 mV from zero, enable SS ZERO. This brings the spring to the center of its range. When the position is within about 20 mV of zero (or stops moving) disable SS ZERO. It is normal for the SS POS value to fluctuate as the reference mass bounces on its spring, but eventually it should damp out, and the fluctuations should be ≤10 mV. At this point, enable SS SERVO.

After five minutes or so, the "scatter" of the spring position should be 1-2 mV on a voltmeter. If the spring is not totally at thermal equilibrium, it is normal for the value to slowly drift in one direction. This is normal and should not affect the measured gravity value (the spring is moving at a constant velocity).

3.2 Software Set Up

Turn the Computer on (COMP POWER on the electronics). See the g User's Manual for a complete discussion of the software and setup procedures. Listed below are some A-10 specific set up notes.

3.2.1 Information Setup

Reference Height- enter the total reference height if Terrain Tripod was used, otherwise enter zero.

3.2.2 System Setup

A-10s 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 Parameters must be set in the same manner using the "Setup" button beneath the Fringe Card box. The recommended settings for a standard A-10 dropper are:

Input Multiplexor: 4
Prescale: 100
Fringes Acquired: 700

A2D card settings must also be entered. For the IO Tech card the recommended settings are as follows:

Table 1. DAQ Card Settings

	Offset	Multiplier
Channel 0	0	100
Channel 1	0	1
Channel 2	0	1
Channel 3	0	1
Channel 4	537.5	125

NAME: DaqBoard2K0

The final change on the system page is to ensure that the "Serial Baro" box is unchecked.

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 A-10). The set interval should be set to your choosing. Finally, note the Pulse Delay -- the time between the lift and drop of the test mass. This should be about 1/3 of the drop interval, or set to a minimum of 0.43 seconds. If the intervals are inconsistent the software will warn you.

A complete discussion of "how much data is enough?" is beyond the scope of this manual, but there are some general rules of thumb. The best answer is to take enough data so that the statistical precision is smaller than the system's systematic uncertainty (~10 μGal). This might require a short test run to determine the drop-to-drop scatter in the measurements (the statistical precision will then be the drop scatter, σ_{drop}, divided by the square root of the number of drops, N). Once the statistical precision is significantly better than the instrument's systematic uncertainties, acquiring more data is not necessary.

Finally, note that the A-10 is designed to be a 10 μGal field instrument. As such, it is not optimized for high precision (<2 μGal) laboratory experiments; those applications are probably better suited to the FG5 absolute gravimeter. Typical set up parameters for the A-10 are listed below:

- Typical field measurements in high-speed production mode (total measurement time ~ 30 minutes):
    - Drop interval: 1 second
    - #Drops/Set: 100 – 150
    - Set interval: 3 – 4 minutes
    - #Sets: 6 – 8

- Typical laboratory measurements (total measurement time 24 hours)
    - Drop interval: 5 second
    - #Drops/Set: 100
    - Red/Blue interval: 10 minutes
    - Set interval: 60 minutes
    - #Sets: 48

Note that, depending on the speed and memory of the system computer, if significantly more data are acquired, acquired more rapidly, acquired with many software windows open, or acquired with "System Response" (see "g" Manual), the software may "crash". If this happens, try slowing down the acquisition, and reducing the load on the computer.

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 and the INIT/RESET light is off (press RESET/INIT until it is off)
- the dropping cart is at the bottom position.
- the laser is in REMOTE (or "COMPUTER") mode, with the left LED illuminated, (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 is on
- AUTOLEVEL is off

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 A-10.

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 raw (the green curve) residuals are relatively flat (<0.5 nm). A large (>5 nm) "sine" wave in the residuals can indicate a problem with the vacuum level – check the ion pump voltage and current.
- 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 (of course, verify that the laser is in REMOTE mode). 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 A-10

3.4.1 Case 1 – Packing While Under Power

If another measurement is desired quickly at a nearby site, it is important to keep the units and the laser at temperature and keep the clock stabilized.

- Close all the windows on the computer, and power the computer down using the COMP POWER button on the electronics.
- Turn SS SERVO off and travel-lock the Superspring (Lower Unit).
- Place the Dropper Controller in RESET mode
- Travel-lock the Dropping Chamber (Upper Unit)
- Place the laser in MANUAL mode and turn LASER LOCK off (Keep LASER POWER on!)
- Keep RUB POWER on.
- Turn AUTOLEVEL on. Use the toggle switch on the Lower Unit to lift the unit back up into contact with the Upper Unit. (Leave the switch in the up position.) Turn AUTOLEVEL off after the units have been re-coupled.
- Loosen, lift, and tighten the Upper Unit tripod legs, and lift it off of the Lower Unit.
- Replace the beam window cover on the Lower Unit.
- Put all Units back in their boxes (keeping cables connected!), secure the units with the straps, and move to the next site.

3.4.2 Case 2 – Packing for Long-Term Storage

If the A-10 is not to be used for a long period, shut everything down with the exception of the ion pump power supply. Even if the instrument is to be stored for a few months, it is better 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 using the COMP POWER button on the electronics.
- Turn SS SERVO off and travel-lock the superspring (Lower Unit).
- Travel-lock the dropping chamber (Upper Unit)
- Turn AUTOLEVEL on. Use the toggle switch on the Lower Unit to lift it back up into contact with the Upper Unit. (Leave the switch in this position.) Turn AUTOLEVEL off when units have re-coupled
- Turn MAIN POWER off and disable control (turn CONTROL ENABLE off)
- Make sure ION POWER is on! (Unless shipping) Note that the LED on the upper right of the Electronics next to the Ion Power switch is illuminated.
- Loosen, lift, and tighten the Upper Unit tripod legs, and lift it off of the Lower Unit.
- Replace the beam window cover on the Lower Unit.

- Put all Units back in their boxes, strap in place, and insert foam wedges.

4 FIELD OPERATION

Though of course the best measurement results can be expected in a stable, laboratory environment, the A-10 is designed to be a field portable instrument. With care in the choice of measurement location and instrument set-up, the A-10 will provide consistent, reliable absolute gravity measurements.

4.1 Environmental Considerations

4.1.1 Ground

Ideally, the A-10 will be located on stable, relatively level ground. Bedrock, or a stable concrete pier, is most desirable, as these provide the smallest micro-seismic signals and will maintain the system's verticality throughout the measurement. A good field technique to determine if a concrete pier or piece of rock is suitable is to strike the site in question with a fair sized rock, or hammer, while placing your palm against the surface roughly a foot away from the place of impact. If you note a vibration or 'ringing' from the impact, the site is not well suited for measuring gravity. A good rule of thumb when measuring on concrete is that the slab should be at least four inches thick, with ideal being several feet in thickness.

If such substrates are not obtainable, find the best location possible giving consideration to vibrations and system verticality (i.e. soft dirt can often "sink" with time, adversely affecting the system verticality).

4.1.2 Weather

- **Temperature**. As discussed, the system is thermally stabilized and designed to run reliably at internal temperatures between –20ºC to 40ºC (though some adjustment to the internal temperature settings may be required. See Section 5.1). At temperatures colder than this, the system will not be able to maintain equilibrium, and it is possible that the dropper mechanism will not work reliably. At temperatures higher than this, there is significant risk of damage to the electronics and laser. On days with high temperatures and clear skies, it is a good idea to shade the meter to prevent the internal temperatures from exceeding the ambient temperature. During times of warm weather it is a good idea to keep a close eye on temperatures of the Drop Chamber and IB (observed with a voltmeter through temperature BNCs on the front of the Electronics) to assure they do not exceed the recommended limits.
- **Wind**. Though the test object is in freefall during the measurement (and therefore insensitive to motions of the Upper Unit during the drop), wind can cause deviations in the laser verticality, adversely affecting the gravity measurement. A convenient solution is to place a simple nylon tent (preferably without a "floor") over the fully-assembled instrument. This is usually sufficient to eliminate the effects of wind.

- **Precipitation**. First, note that the electronics rack and computer system are in no way weather resistant. The dropping chamber and I.B. units, however, are nominally water resistant, though care should be taken to avoid allowing water in through the top of lower unit (at the holes containing the three "Vees"). Of course, care should also be taken to avoid getting water in the cable connections at both sensor heads. It is generally best to cover the instrument with at least a small nylon tent in inclement weather (and required if it is actually raining or snowing). This will also help avoid small changes in verticality if the system were to accumulate precipitation.

4.2 Vehicle and Power Considerations

While it is possible, and indeed common, to operate the A-10 from an AC battery charger in a laboratory, the A-10 is designed to be deployed easily from a vehicle. The type of vehicle is not important, though it needs to be able to fit all the boxes (including, in general, the turbo pump box).

When deploying from a vehicle, the ideal situation is to have a "station" in the vehicle where the operator can easily monitor the electronics rack and computer system during the measurement. In addition, it is most convenient to have the deployment boxes arranged so that the two sensor units can be easily placed in and out of the vehicle.

4.2.1 Deployment Boxes

Figure 12 shows the deployment/shipping boxes. Each sensor unit has its own specific box, and the unit only fits in that box one way.

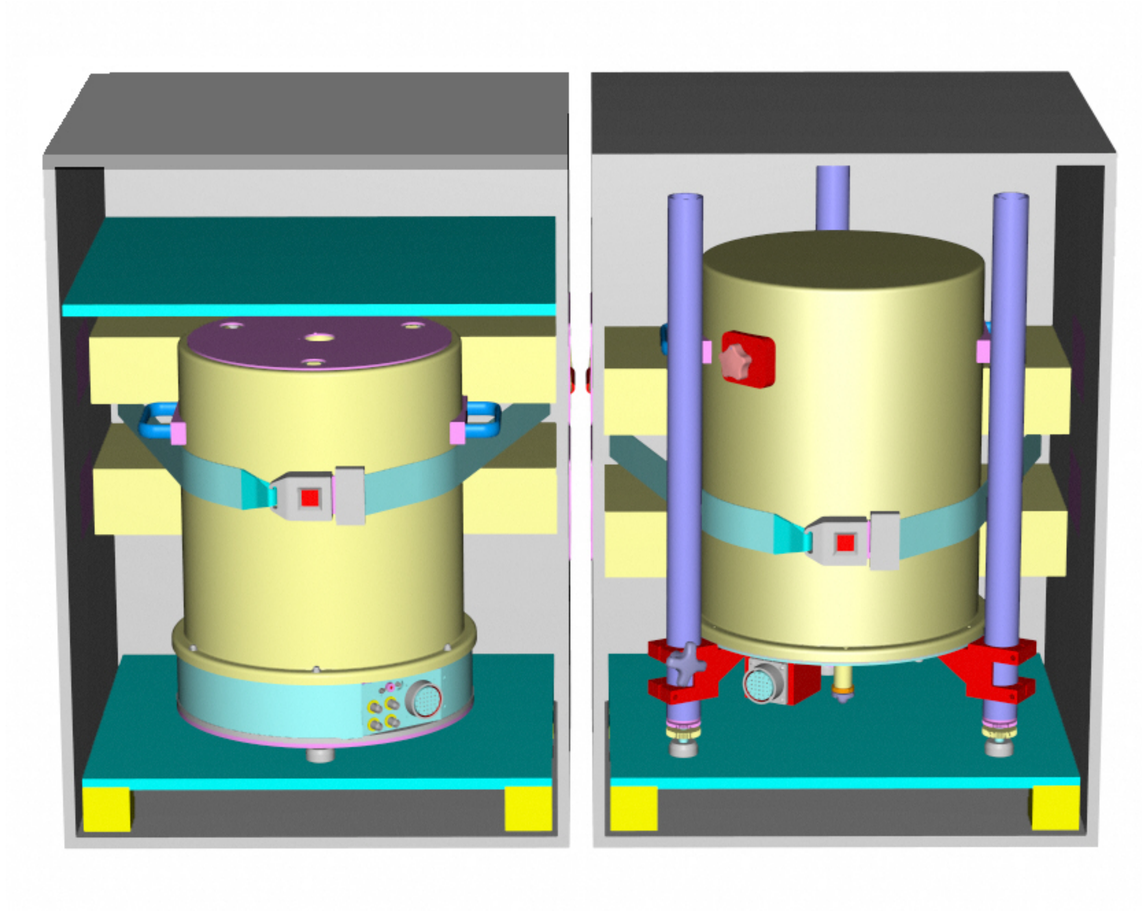


Figure 12. A-10 Boxes in Deployment Mode.

- During shipping, the straps should be engaged and a large block of foam should be wedged between the top of the box and the sensor unit. The cables should be disconnected and placed in the shelf of the box for the Lower Unit. Both front doors should be securely latched close.
- During deployment from a vehicle, it is usually only necessary to engage the straps. Normally it is desirable to leave the cables connected and the box doors off.

4.2.2 Cables

The A-10 system is designed so that the instrument can be set up well away from the vehicle and operated from within the vehicle. The cables are usually 18 m long. When coiling (or uncoiling) the cables back into (out of) the vehicle, take care not to stress the ends of the cables, or the sensor connections. Also, try to avoid getting the cables "twisted up" – this can damage the fragile wires inside the cables. Finally, take special care in not damaging the 50 Ω cable that is used for the TTL fringe signal. A kink can cause a change in impedance which can actually change the measured gravity value.

4.2.3 Using a Vehicle Battery

During an average load (i.e. when the system is already warmed up and at thermal equilibrium), the A-10 draws approximately 16A at 12V. **Note that the computer uses by far the largest amount of power. Power it down when possible to conserve battery charge.** With a standard car battery this means only a few hours of continuous operation. Depending on the measurement time, it is generally considered best to turn the vehicle off during actual data acquisition to reduce induced vibrations, but this is not absolutely necessary. In practice, it is best to start the vehicle between measurement sets to recharge the battery. It is best to use a vehicle with a secondary battery (connected with an inline diode that allows the vehicle's alternator to charge the battery without draining the primary battery), and connect the A-10 to this secondary battery.

If the system is to be left at operating temperature overnight it will most likely be necessary to use an AC battery charger (run from an extension cable). See Section 4.2.4 for AC Battery Charger information.

4.2.4 Using an AC Battery Charger

When operating the A-10 in a laboratory with a 12V battery and a charger, note that, depending on the circumstances, the A-10 can draw wildly varying amounts of current:

- Full Power (while coming up to operating temperature): 25A
- Average Power (maintaining operating temperature): 16A
- Ion Pump only: 0.25A

Ideally, the charger will allow you to set the charge current appropriately. This will increase the life of your battery. It is important to occasionally measure the voltage across the terminals of the battery when the charger is connected to **insure that the voltage to the instrument does not exceed 15 Volts. Damage to the instrument can occur above this voltage!** If you measure greater than 15 volts, you may have a defective charger, or the battery may need replacing.

4.2.5 Using an (optional) laboratory AC Power Supply

When operating the A-10 in a laboratory, it is most convenient to purchase an optional AC – DC power supply. In this case 100 – 240 VAC (50/60 Hz) can be converted directly to 12 VDC and connected to the A-10 electronics via an Andersen connector cable. No charging, nor monitoring of voltage or current is necessary. For more information, contact Micro-g LaCoste.

4.2.6 Maintaining Chamber Vacuum

Between measurements, even if it is a few months, it is recommended to maintain the vacuum by leaving the ion pump powered on. This saves baking and turbo-pumping time. Rather than powering up the electronics and connecting the large cable for the Upper Unit, there is an auxiliary 12VDC input on the Unit can (See Figure 13). Using the supplied cable, any 12VDC power supply (capable of at least 0.5A) can be used to power just the ion pump. Of course, when the electronics rack is powered up and connected to the can via the large cable, this should be used to power the ion pump.

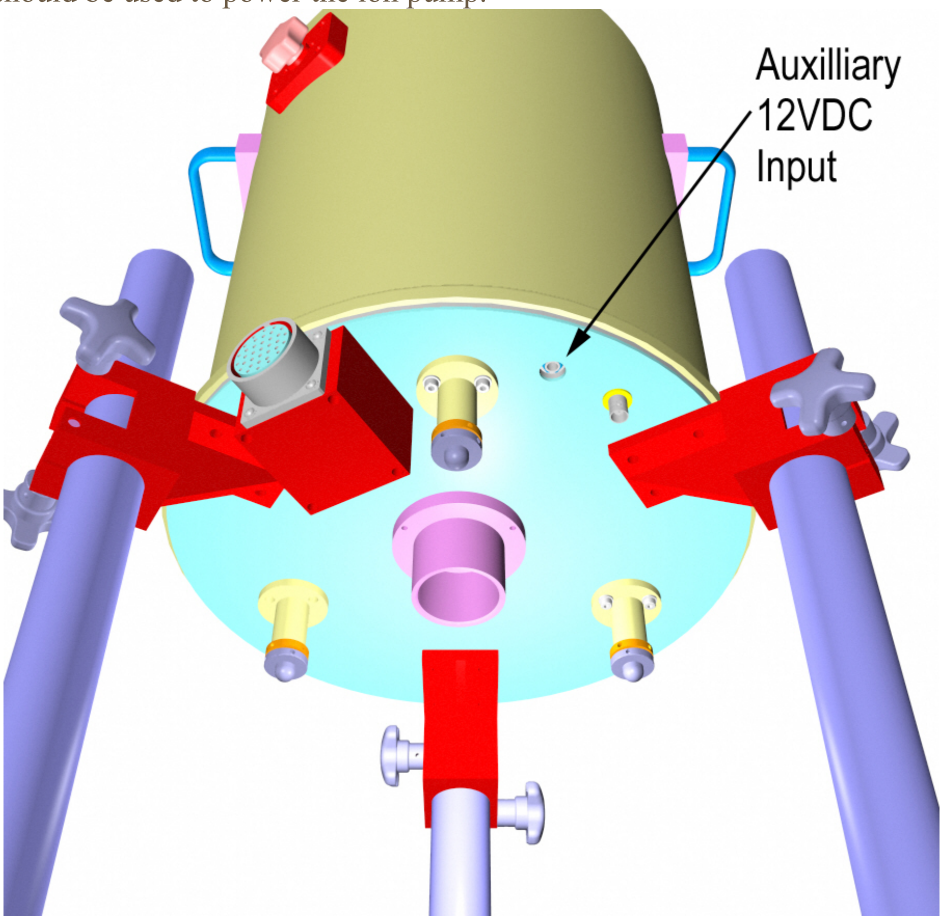


Figure 13. Location of auxiliary 12VDC input. This is used to maintain ion pump power while main electronics are disconnected. Note- Do not use this input if the ion pump has been of for more than 24 hours, or if the state of the vacuum is unknown. Powering up the ion pump with an excessive vacuum will seriously degrade the life of the pump.

5 SYSTEM ALIGNMENT AND OPTIMIZATION

5.1 Setting the A-10 Temperatures

The A-10 is temperature-stabilized to allow reliable operation of the instrument in widely varying environmental conditions. There are three separate, thermally controlled zones in the two A-10 units (it is assumed that electronics and system computer are in a reasonably warm and safe environment such as the inside of a van or truck, for example):

- The dropping chamber can temperature (Upper Unit)
- The superspring/interferometer temperature (Lower Unit)
- The laser housing temperature (Lower Unit)

The current temperature for each of these systems can be monitored at the BNC outputs on the main control panel. Understanding the temperature control, coupled with the knowledge of the temperature set points, will allow you to determine when the system has reached thermal equilibrium, insuring reliable operation.

Finally, note that in most field surveys (in ambient temperatures ranging from 20-33ºC) it is usually unnecessary to adjust the A-10 temperature settings.

5.1.1 Setting the Dropping Chamber Can Temperature (Upper Unit)

The dropping chamber is unique in that temperature only becomes a problem at the far reaches of the instrument's temperature range. The motors and feedthroughs that operate the Dropper start to function poorly at low temperatures, while above 40ºC the ion pump becomes significantly less efficient. If it is deemed necessary to adjust the temperature control of the Drop Chamber, open the Upper Unit cover, and locate the circuit board on the side of the dropping chamber. While using a voltmeter to monitor TP5 (-10mV/ºC), use a screwdriver to adjust pot R12 to set the desired temperature. This potentiometer controls the temperature of the heat tape around the drop chamber. R8 controls the block heaters located inside the can, and it is important that these heaters be set to an equal value to R12. With a voltmeter, monitor TP3 while adjusting R8 to the same value as R12.

5.1.2 Setting the Superspring/Interferometer Temperature (Lower Unit)

Unlike the case of the dropping chamber (where fluctuations above a minimum temperature are of no concern), the temperature of the superspring and interferometer needs to be precisely controlled. The main reason for this is the temperature dependence of both the inclinometer output (important for system verticality) and the Superspring test mass position. There is no active cooling system in the A-10, so all temperature control is achieved with heat. Therefore, to compensate for temperature fluctuations in the environment, it is important that the controlled system temperature be above the ambient temperature. While the exact temperature difference is not crucial, the **Superspring/Interferometer** temperature should be set **at least 5ºC above** the hottest ambient temperature expected during the measurement.

To set this temperature, open the Lower Unit cover, and locate the circuit board on the side of the Superspring. There is a label indicating "can" or "spring" temperature for both a screwdriver and a voltmeter probe. While monitoring the set temperature on the voltmeter (-10mV/ºC), adjust the screwdriver until the desired set temperature is achieved. Replace the cover and turn on the IB TEMP control using the main control panel.

After changing the temperature, and letting the system reach equilibrium, it is important to use the beam checker (Section 5.3) to check the system verticality and adjust if necessary.

5.1.3 Setting the Laser Temperature (Lower Unit)

Like the Superspring/Interferometer temperature, it is important that the temperature of the laser be controlled precisely. The frequency of the laser is quite dependent on the temperature and changes in temperature. Again, it is important that the controlled laser temperature be above the ambient temperature. While the exact amount of temperature difference is not crucial, the **laser** temperature should be set **at least 10ºC above** the hottest ambient temperature expected during the measurement. This temperature is normally set to around 50ºC at the factory.

To set this temperature, open the Lower Unit cover, and locate the circuit board on the side of the superspring. There is a label indicating "laser" temperature for both a screwdriver and a voltmeter probe. While monitoring the set temperature on the voltmeter (-10mV/ºC), adjust the screwdriver until the desired set temperature is achieved.

5.2 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.

5.2.1 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.

5.2.2 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.

5.2.3 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.

5.3 Checking Beam Verticality

It is imperative that the laser beam be vertical with respect to the local gravity field. Deviations from verticality always result in a gravity measurement that is too low (and the error is proportional to the square of the deviation angle). In order to check the verticality of the laser beam, the Upper Unit must be removed and the beam checker put in its place on top of the Lower Unit with AUTOLEVEL ON. The beam checker is pictured in Figure 14.

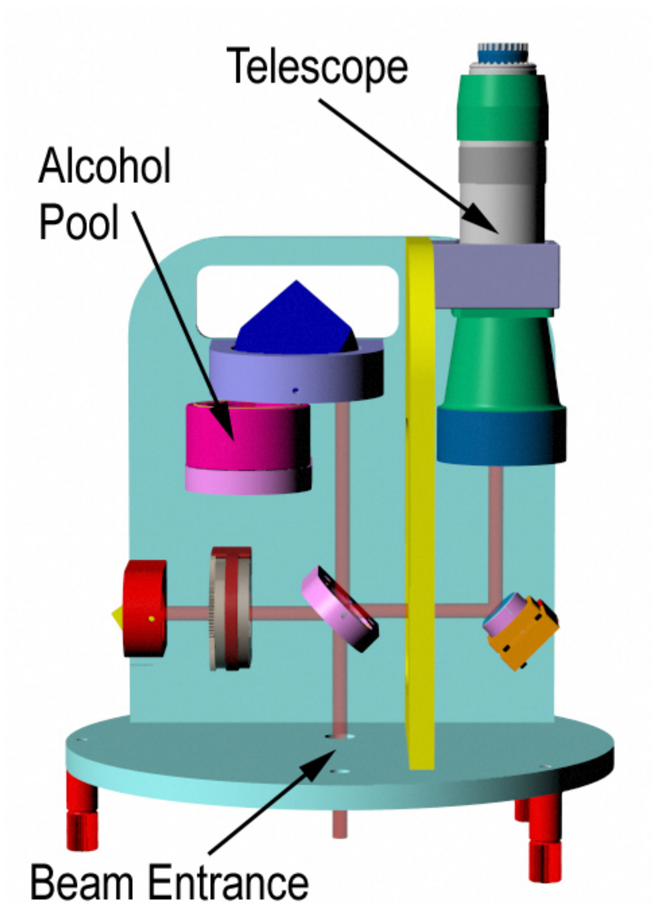


Figure 14. Vertical Beam Checker. The beam enters from below and is split into a reference beam and a test beam that bounces off the surface of an alcohol pool. The recombined beams are viewed in the telescope. The angle of the original beam is adjusted until the two beams form a single spot in the telescope.

The laser beam enters through a hole in the base and is split into two beams. One beam, the reference beam, travels horizontally to the lower corner cube and is reflected back on itself, through the splitter (and a polarizer to reduce its intensity), and into the telescope. The other beam, the test beam, travels up from the first splitter, into the upper corner cube, and off of the surface of an alcohol pool (whose surface is, of course, perfectly level). The test beam is then recombined with the reference beam at the splitter and also travels into the telescope. The telescope is focused to infinity, meaning that parallel rays form a single spot in the telescope. Therefore, when the initial beam is perfectly vertical, the two spots (reference and test) form a single spot in the telescope.

To use the beam checker, slide the unit around until the laser beam is coming up through the hole in the center of the beam checker base. While looking in the telescope, slightly move the beam checker until the reference beam forms a distinct "asterisk" (*) . This indicates that the reference beam is traveling to the exact center of the lower corner-cube. Place the alcohol pool in the unit, and after the surface of the pool settles down, the two spots should form a single spot in the telescope. Note that this procedure might be difficult, if not impossible, to perform in outdoor weather conditions.

Though the system is aligned at the factory, it is possible that the two beams will not form a perfect spot (during normal operation, the spots should always be well within a ½-spot diameter of each other). Normally, this is due to the slight temperature dependence of the inclinometers that sense system verticality. That is, if the system is set to run at a different temperature than normal, or if it is not fully at thermal equilibrium, the inclinometers will not bring the system to true verticality. To adjust such a misalignment, turn AUTOLEVEL ON, and locate the two potentiometer screws near the separation switch on the Lower Unit (See Figure 15). While looking in the telescope, use a screw driver to adjust each of these screws as necessary to drive the system to verticality. These screws are attached to the circuit that levels the A-10, and this procedure effectively "resets" the inclinometers to define the new level. For the reasons mentioned above, this procedure should only be performed when the system is at thermal equilibrium.

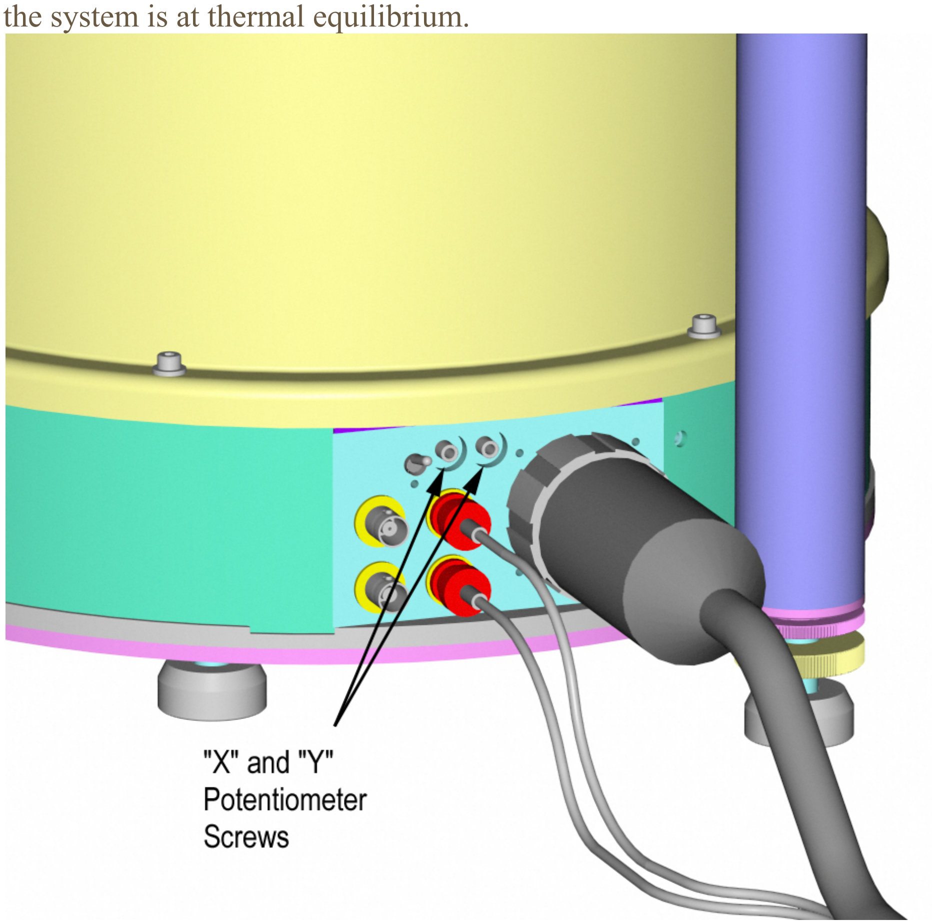


Figure 15. Location of "X" and "Y" potentiometer screws.

5.4 Aligning Interferometer and Superspring

For the A-10 to function correctly, the three main components---dropping chamber, interferometer, and superspring---need to be aligned precisely at the same time that the beam is vertical. If you know, or suspect, that something is out of alignment, perform the following steps (ideally, the unit is in thermal equilibrium at its operating temperature):

- Remove the can from the Lower Unit (the interferometer).
- Turn AUTOLEVEL on.
- Locate the two screws that adjust the level of the interferometer plate relative to the rest of the Lower Unit. With AUTOLEVEL on, adjust these screws so that the two bubble levels on the Superspring are centered when the system is level.
- Check beam verticality.
- If the beam is not vertical (outside of approximately one beam diameter):
  - While monitoring the Vertical Beam Checker, adjust the two screws on the optical mount at the output of the laser fiber until the beam is vertical.
- Verify that the two beams are centered on the photodiode as discussed in Section 5.5
- After replacing the can, it is a good idea to allow the unit to thermally stabilize (roughly 30 min-1hour depending on conditions, and for how long the can was removed), and then perform another check of verticality.

5.5 Steering the Beam Onto the Photodiode

It is important that the overlapped test and reference beams are centered on the photo-detector. As shown in Figure 16, the beams are steered onto the photo-detector by a small mirror that deflects the beams 90º (the beams then go through more optics, including a focusing lens, but the alignment is governed by the 90º mirror angle).

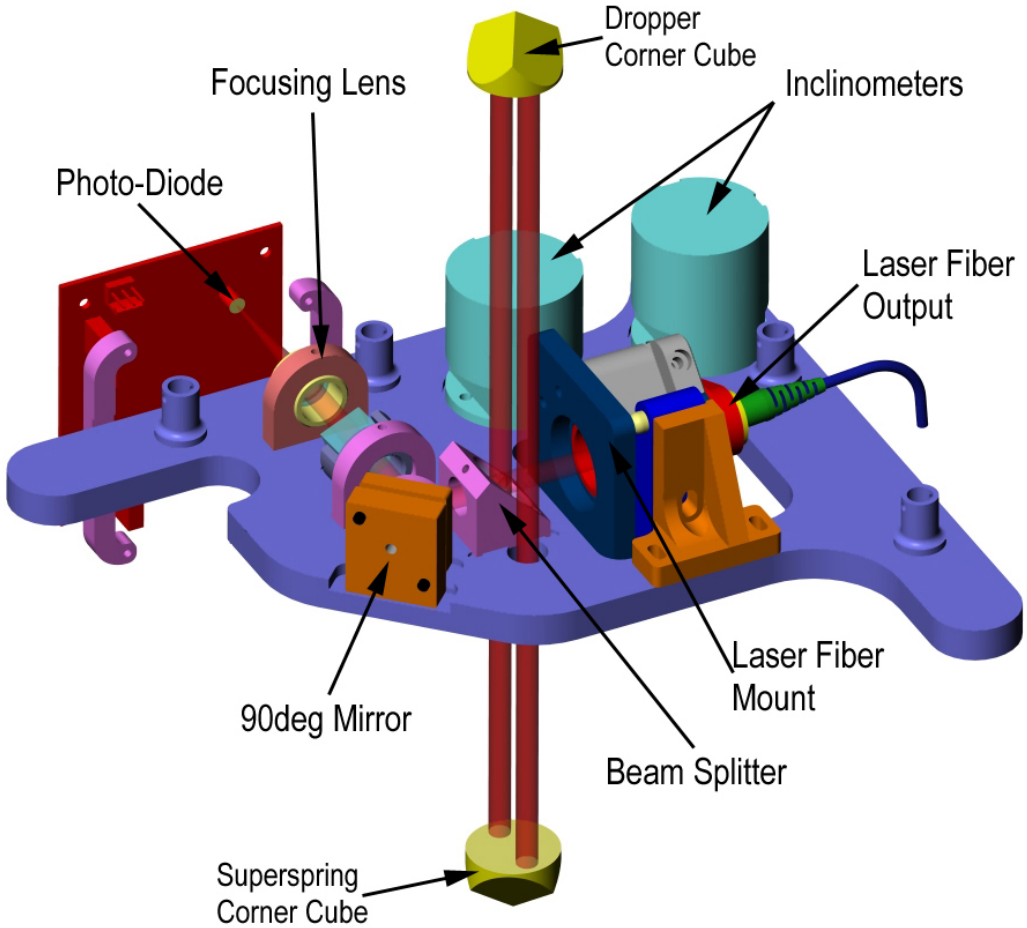


Figure 16. A-10 Interferometer Schematic.

To determine whether the beam is striking the center of the detector, remove the can from the Lower Unit, and then connect an oscilloscope, or voltmeter, to the analog fringe BNC on the A-10 control panel (or on the upper right BNC on the Lower Unit). Set the oscilloscope to approximately 1V/div vertically, 1s/div horizontally, and DC coupling. The PIN photodiode is reverse biased meaning that more light on the detector causes a more negative voltage. With no light on the detector the analog signal should be about 0.2 V, and with the beam on the detector, the signal should be about –0.5 V. Block the test beam (up to the dropper), and only use the reference beam to perform this operation. While monitoring the signal on the oscilloscope, slowly move the mirror left and right, and then up and down, sweeping the beam across the photo-detector. You should see an inverted "plateau" as the light comes onto the detector at one side (lowering the voltage) and then going off the other side (raising the voltage). By noting the position of the mirror adjustment screws, it possible to go back to the center of this inverted plateau. Adjust the mirror both vertically and horizontally until the position of the beam is centered in both directions. It is best to iterate the procedure about three times.

5.6 Final System Alignment

To obtain maximum fringe signal amplitude, it is necessary that the two beams (test and reference) be perfectly collinear. To verify this, observe the two beams after the 90º mirror. By blocking and unblocking the test beams before it enters the dropping chamber (with a piece of paper), it is possible to determine the overlap of the beams. If the two beams are noticeably non-collinear, loosen the 9 screws that hold the three inner feet of the Upper Unit (see Figure 17). Translate the Upper Unit relative to the Lower until the beams are collinear.

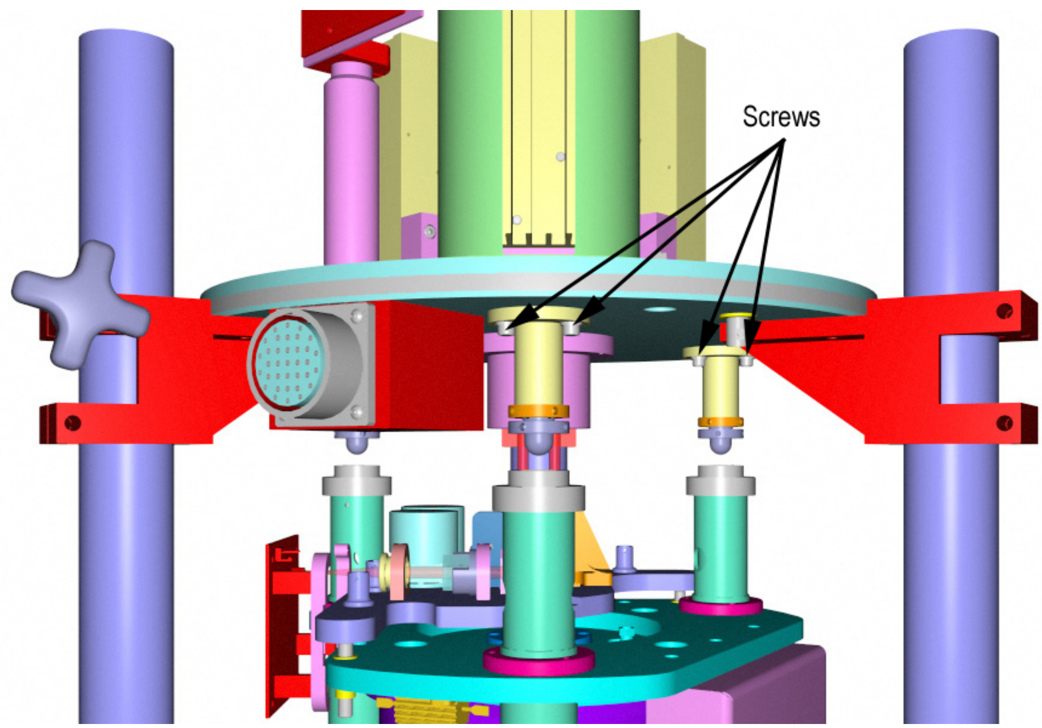


Figure 17. Screws that allow translation of the dropping chamber relative to the interferometer. Note that there are 9 in total.

Verify that the two beams are centered on the photodiode as discussed in Section 5.5. Then tighten the 9 screws on the Upper Unit feet.

5.7 Regular System Maintenance

While designed to provide reliable data over a long time, like any sensitive equipment, the A-10 does need to receive maintenance at regular intervals. While the exact interval will depend on many variables, typically the system will need service after approximately 1 – 2 years or 500,000 to 1,000,000 drops. A list of typical Micro-g LaCoste maintenance items is given below:

- Laser calibration
- Rubidium Clock calibration
- Test-mass ball & vee balance and replacement
- Cleaning of optical components
- Determination of ion pump and feedthrough lifetimes
- Electronic circuit tuning (dropper, Superspring, and leveling system)
- Complete instrument operation verification

6 VACUUM CHAMBER: Turbo Pump and Baking Out

Under normal operations, the vacuum in the A-10 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.

6.1 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 18.

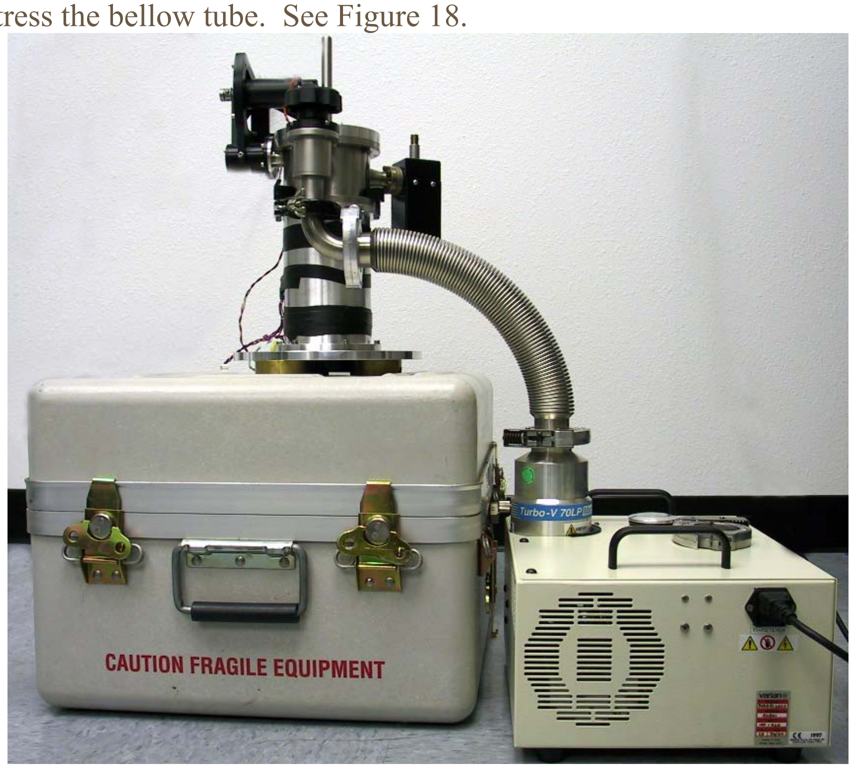


Figure 18. Turbo pump connected to dropping chamber. Note the minimum stress in the hose.

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.

6.2 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.

6.2.1 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, remove the can from the Upper Unit. Make sure the travel lock is engaged (this allows thermal contact between the test mass and the chamber). Locate the circuit board on the side of the dropping chamber (this is the same circuit board used to adjust the can temperature in Section 5.1.1). Set R8 to 60ºC (monitoring with a voltmeter on TP3, -10mVolts/ºC). Set R12, monitoring through TP5, to room temperature. Activate DROP TEMP on the Electronics. The temperature should be monitored to make sure things are functioning properly.

For best results, wrap an electrically non-conducting insulator (bubble wrap or a blanket) around the exposed dropper unit while baking out. Without such insulation, the maximum temperature reached is typically only 45-50ºC. **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.

6.3 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 (note that the voltmeter indicates the true voltage /1000, so 4.0V on the voltmeter indicates 4kV at 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 of approximately 0.1 to 0.5 V) 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). Note that the absolute value of the current is not important (each ion pump is different and will draw a different current). The important thing is that the value is stable or slowly decreasing.

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.

NOTE If the ion pump voltage immediately goes to 4 kV without "ramping up", this could indicate a possible open in the ion pump circuit. This means the ion pump is at full voltage, but is not actually ionizing any molecules (i.e. it has not started "pumping"), and the current it draws will be very near zero. In this situation **the ion pump is possibly not ready!** Leave the turbo pump on with the valve open at this point. Next take a hard object (i.e. a screwdriver) and gently, but firmly, tap the ion pump (not the controller). This can release molecules in the ion pump and start the ionizing process. If successful, you should see the ion pump voltage drop noticeably and then slowly ramp back up to near 4 kV. The current should now also be non-zero. This indicates that the ion pump is functioning.

7 Electronics Connections

Below is a list of the basic connections needed to measure gravity with the A-10. (Note that when shipped from the factory, the cables that connect the various A-10 electronic components are labeled.) This list does not include various diagnostic connections that might need to be made during set up or debugging: fringe amplitude, inclinometer readings, etc.

7.1 Control Center

- Front
  - SS POS (Superspring Position) ↔ Patch Panel: CH01
  - ION CURR (Ion Pump Current) ↔ Patch Panel: CH02
  - LASER CURR (Laser Current) ↔ Patch Panel: CH03
  - BARO (Barometer voltage) ↔ Patch Panel: CH04
  - LASER LOCK ↔ Patch Panel: LASER LOCK
  - LASER MODE ↔ Patch Panel: DIG C5
- Back
  - 12 VDC Input ↔ Battery/Charger
  - 12 VDC Output ↔ DC Input on Computer
  - Lower Unit (IB) Cable ↔ Lower Unit (IB)
  - Upper Unit (Drop Chamber) Cable ↔ Upper Unit (Drop Chamber)
  - Analog Fringe In/Rear Dropper controller ↔ Lower Unit Cable (upper right BNC)
  - TTL Fringe In ↔ Lower Unit Cable (lower right BNC)
  - 10 MHz Out ↔ Computer: CLOCK
  - TTL Fringe Out ↔ Computer: FRINGE
  - Patch Panel Power ↔ Patch Panel: POWER (rear)
  - Dropper Controller Power ↔ Dropper Control: POWER (rear)
  - Dropper Controller Control ↔ Dropper Control: CONTROL (rear)

7.2 Patch Panel

- Back
  - Analog/Digital Cable ↔ Computer: A2D Card

7.3 Dropper Controller

- Front
  - TRIGGER IN ↔ Patch Panel: TRIG OUT
  - TRIGGER OUT ↔ Computer: TRIG
- Back
  - IN/OUT ↔ Analog Fringe In

8 System Specifications

8.1 Power

- 12-14 V DC
    - Computer 8A
    - Upper Unit 8A full load 3A average load
    - Lower Unit 8A full load 4A average load
    - Electronics 1A
    - Ion Pump 1mA
- Full load 25A 300W
- Average load 16A 200W

8.2 Weight and Dimensions

- Weight
    - Upper Unit 19kg
    - Lower Unit 21kg
    - Electronics 21kg
    - Computer 12kg
    - Cables 7kg (each)
    - Deployment Boxes 25kg (each)
    - Total 105kg

- Dimensions
    - Can diameter 30cm
    - Footprint diameter 50cm
    - Assembly height 90cm
    - Cable length 15.5m

8.3 Operating Temperature

- -18ºC – 38ºC (0ºF – 100ºF), internal temperature

8.4 General Specifications

- Accuracy: 10µGal (Absolute)
- Precision: 10µGal in 10 minutes (at a quiet site)

9 Warranty

The warranty covering the FG5 Absolute Gravimeter is as follows:

Micro-g LaCoste, Inc. hereby warrants to purchaser that the instrument delivered hereunder shall be free of defects in material and workmanship appearing within one year from the date of delivery. Purchaser, or any third party purchaser, must give written notice of any defect covered by this warranty to seller within 13 months of the date of delivery of the instrument to purchaser. For any defect covered by this warranty, seller shall repair or replace defective components of the instrument on a timely basis at its sole expense provided that such warranty service shall be performed by seller at its facility in Lafayette, Colorado, U.S.A., and all cost of returning the instrument to seller shall be borne by purchaser. This warranty does not cover labor costs and other contingent expenses incurred by purchaser or a third party for the diagnosis of defects, and does not extend to the instrument if it has been (a) subject to misuse, neglect, accidents, acts of God or causes of a similar nature, or (b) altered by anyone other than seller without seller's prior approval. This warranty is in lieu of all other warranties except seller shall pass through any warranty issued by a manufacturer of any component part of the instrument and subrogate purchaser with respect to any claims thereunder.

This warranty is expressly conditioned on the following performance by the purchaser during the warranty period:

I. In repairing or replacing component parts in the instrument, purchaser shall use only the following parts:

A. parts supplied by seller;

B. parts obtained from third parties to the extent such parts were made by the same manufacturer as the part being replaced; and

C. similar parts, upon prior written approval of seller, which approval shall not be unreasonably withheld.

II. During the warranty period set forth above, purchaser shall give seller prompt notice of any and all problems associated with the operation or integrity of the instrument.

Quick Set-up/Take-down

Setup

- Check that ion pump is powered on and operating correctly
- Check that battery (12V source) is fully charged
- Connect cables (12V source, IB cable, and dropper cable)
- Set temperatures
  - IB Temp (Superspring): ~6°C above ambient
  - Laser Temp: ~12°C above ambient
  - Dropper Temp: ~20°C
- Laser power ON
- Temperature control ON (if off for a while, wait ≥4 hours to stabilize)
- Rubidium clock ON
- Place and level tripod at measurement location (if necessary). Measure "reference height"
- Place IB on tripod (if necessary)
- AUTOLEVEL ON. Make sure IB is in "upper" position
- Use beam checker to verify verticality, adjust pots if necessary (with AUTOLEVEL ON)
- Place dropper on top of IB
- Unlock travel lock on dropper unit (turn knob, and pull out to disengage lock)
- Lower the legs, use the separation toggle switch to lower the IB, turn auto level OFF
- Unlock the Superspring
- 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)
- Turn off vehicle engine (if necessary)
- Take data

- ❑ ***Tear Down (Survey mode)***
- ❑ Turn on vehicle to charge battery (if necessary)
- ❑ Set dropper controller to RESET
- ❑ Superspring servo OFF
- ❑ Travel lock Superspring
- ❑ Travel lock dropper
- ❑ Verify that laser lock is OFF
- ❑ Back up data (if applicable) and turn computer power OFF
- ❑ Auto level ON, separation switch to lift IB up, then auto level OFF
- ❑ Pack IB & Dropper units in boxes

- ❑ ***Tear Down (Long term)***
- ❑ 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
- ❑ Rubidium clock OFF
- ❑ Temperature control (IB and Dropper) OFF
- ❑ Auto level ON, separation switch to lift IB up, then auto level OFF
- ❑ Main power OFF and control enable OFF
- ❑ Disconnect all cables (but get power to ion pump!)
- ❑ Pack IB & Dropper units in boxes and coil cables