

Appendix B

Pressure sensors (Microphones)

Mr. Adam Norberg deserves a lot of credit for the text and development of the procedure outlined therein.

B.1 Introduction

A set of eight microphones is desired to quantify the amplitude of excitation delivered to the free shear layer of an isothermal combustor. To achieve maximum accuracy a set of Bruel & Kjaer microphones could be used, however these units come at a high cost. As a more economic solution to the measurement requirements it was decided to use a set of Panasonic condenser microphone cartridges. By calibrating them to one highly accurate B&K microphone they can become accurate and precise measuring devices.

B.2 Design

For the acoustic pressures expected during this project, it was determined that the Panasonic WM-034BY Cartridge type condenser microphone was a suitable choice. The WM-034BY is an omnidirectional microphone with a frequency range of 20-16,000Hz and a sensitivity of -42 ± 3 dB. Figure B.1 shows the electrical schematic of the cartridge itself and the additional components recommended by Panasonic. These components are a 2.2k resistor (RL) and a 10nF (or larger) capacitor (C). All three items, the resistor, capacitor, and cartridge are contained within the microphone assembly shown in Figure B.2.

For each assembly, a section of threaded rod was bored out with a lip inside to hold the cartridge. Half inch threaded rod was used with a nut to allow rigid mounting to the test section which has matching threaded holes. The mounting also provides a fast means of changing the location of any microphone. Tightening the nut on the assembly after installation ensures a rigid fit. Signal connection consists of BNC connectors to simplify and strengthen connections external to the assembly. Of the pair, the larger diameter is for the supply voltage and the smaller is the

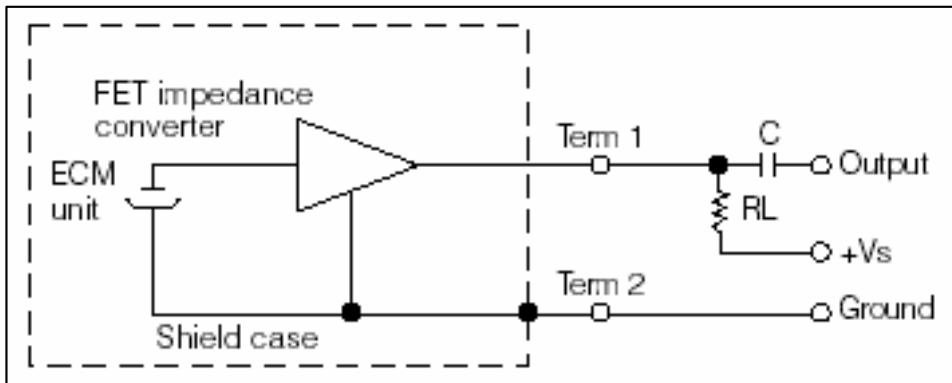


Figure B.1: Condenser microphone internal and external circuit layout



Figure B.2: Complete microphone assembly

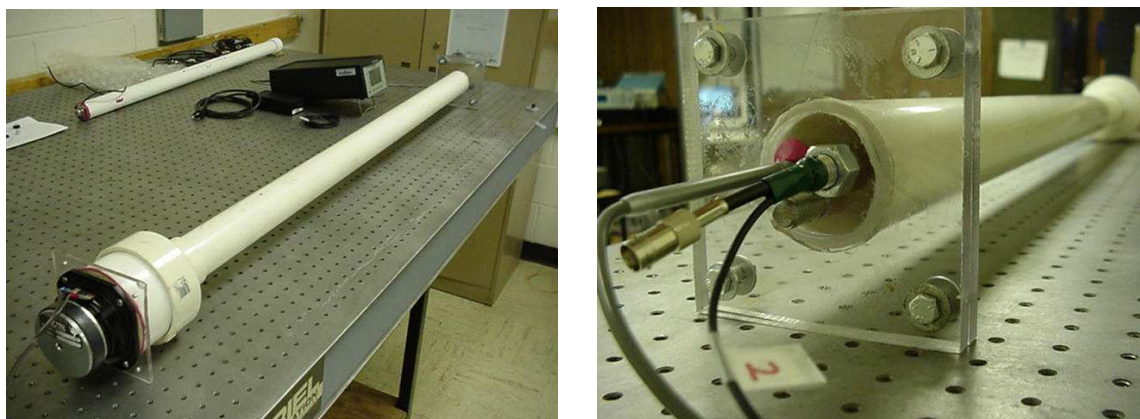


Figure B.3: Microphone calibration rig

microphone output. The leads can easily be stressed by connected cables and cause loose connections within the assembly. As an effective solution, more electrical tape was added to the wire lead end of the assembly to provide extra stiffness.

B.3 Calibration

Panasonic states that the sensitivity of each microphone can vary up to 3dB from the nominal value of -42dB. To determine the sensitivity more precisely, the set must be calibrated to a known reference. A Bruel & Kjaer microphone and amplifier were used as this reference. To provide the acoustic excitation for the microphones the calibration rig shown in Figure B.3 was used. This rig was designed to establish plane waves at the microphone location. Plane waves are desired because all acoustic variables including pressure are constant across a plane perpendicular to the direction of propagation of the wave. By establishing a plane wave in the calibration rig equal pressure signals reached both microphones. The waves are in phase and of the same magnitude allowing a direct comparison between the sensors.

The rig is in a closed-driven configuration with a 4" speaker as the driver and a plexiglas flange at the closed end. Two holes are located in the flange, equidistant

radially from the pipe center. These holes mount the B&K microphone and one microphone assembly, as shown Figure B.3. To ensure the establishment of a plane wave, the pipe was chosen with a radius much smaller than the length of the shortest wave being measured. The pipe must also be rigid which is a valid assumption considering the low amplitude of acoustic power being used. Another reason that a plane wave can be assured is the length of the rig. At large distances from a source, acoustic waves become planar. Since for this rig the ratio D_{source}/L is much less than one, a plane wave assumption is justified.

To perform the calibration a transfer function measurement is performed between the reference microphone (B&K) and the microphone to be calibrated. Random noise was used as the input to obtain a complete band of calibration information in a frequency range of interest. A 3200 series HP analyzer was used to collect the frequency response data and issue the random noise excitation. The data was then read into Matlab for further analysis. To obtain the true microphone sensitivity in V/Pa, the measured transfer function had to be multiplied by the effective reference microphone sensitivity which for this case was 0.0473. Figure B.4 shows the calibration curves for three sample microphones. The microphones were equipped with 0.1 micro Farad capacitors to achieve the lowest possible frequency response. The frequency range of interest was limited here to 0-100 Hz. It can be seen that the microphones show relatively even sensitivity over the range from 20 to 100 Hz. Some interference from power supply noise can be identified at 60 Hz. The measured sensitivity is above the factory quoted sensitivity of $-42dB \pm 3dB$. The reason for this is that the excitation voltage used here, 5.1V is higher than the factory reference excitation voltage of 4.5V. The phase response is somewhat more uneven but here still, all the microphones behave similarly and the voltage signal appears to be very close to 180 degrees out of phase with the pressure wave for nearly the entire range of frequencies.

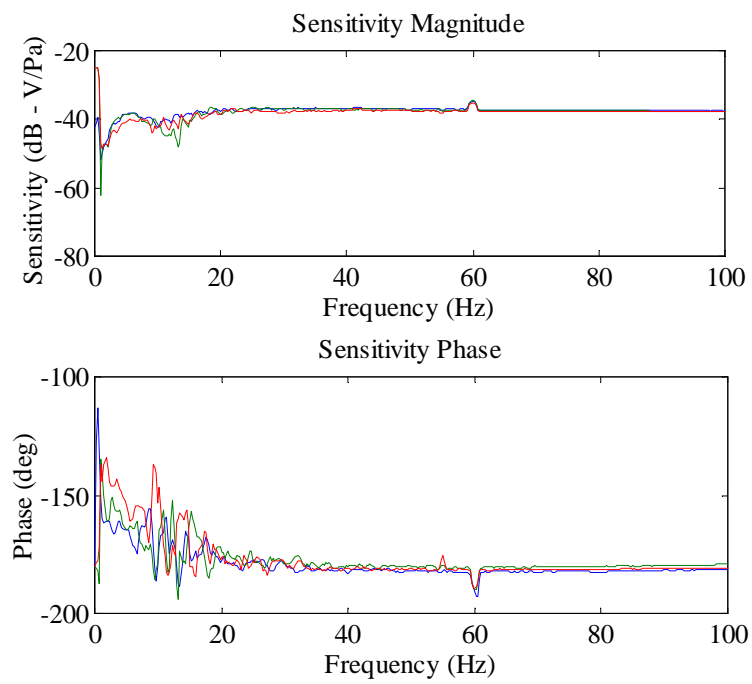


Figure B.4: Sample microphone calibrations

Appendix C

Stepper motors and translation stages

C.1 Introduction

Stepper motors and translation stages are frequently used in VACCG and RFL experiments whenever point measurements must be made over a set grid of measurement points. Stepper motors allow automated and accurate positioning of measurement probes. The typical translation stage setup is shown schematically in Figure C.1. In order to control the translation stage, the computer sends out digital step, direction and disable signals. These logic signals are then interpreted by the stepper motor driver which draws current from the power supply and redirects it to the appropriate winding of the motor. The rotation of the motor can be controlled to 1.8° steps for most common stepper motors. The rotation is converted to translation using a lead screw that is attached to the motor shaft using a coupling. As the lead-screw turns, a special type of nut, called 'anti-backlash' nut travels up and down the lead-screw. The nut is attached to a carriage and the carriage motion is restricted to the rail it is mounted on. Each of these components will be described in the following sections with regard to design, use and replacement.

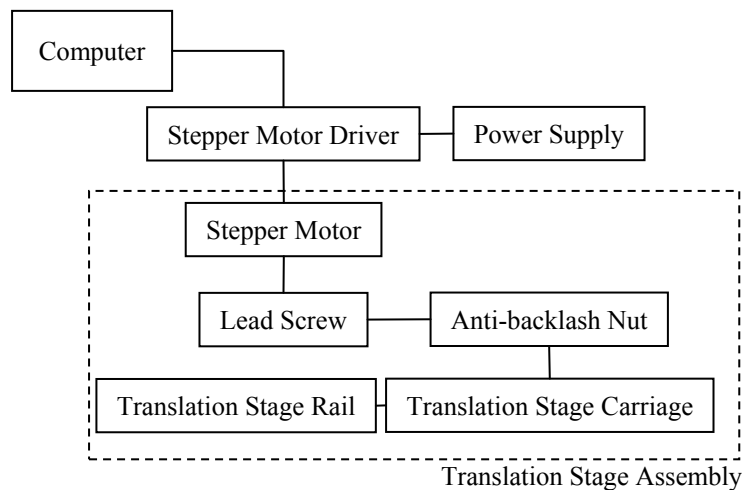


Figure C.1: Translation stage setup

C.2 Computer Control

C.2.1 Motor Control under DOS

Traditionally, the control of stepper motors has been implemented through the parallel port. Using the data port and control port parts of the parallel port as well as C code using (`_outp`), the appropriate digital signals are sent to the stepper motor controller. Several versions of the C code exist. One of the versions is attached to this document. The code is reasonably well documented and can be adapted easily to fit any particular test requirements. In principle the code sets certain data bits on the parallel port to high or low to enable the motor and set the direction. The step signal is also issued through the parallel port. The timing or frequency of the steps is controlled by executing the digital write operations in a loop whose length can be controlled. In other words, for the high part of the pulse, the port is updated x times with same digital value. For the low part of the pulse, the port is again updated x times with the digital value for the low part of the pulse. The higher the value of x the longer the pulse. The value of x appropriate depends on the compiling options used (optimization) and on the computer hardware itself (processor speed). In general, a value of several thousand will work.

For each setup the number should be optimized for smooth operation. As x is decreased from some high value, the motor will stop taking individual small steps and begin turning smoothly. If x is decreased further, operation will again become ragged. The final test of a certain value of x should be a repeated back and forth step operation. The back and forth step operation should be repeated about 100 times and cover a significant travel range ($\tilde{1}$ in). If the speed setting (x) is adequate, the starting and ending points for the back and forth operation will not shift. If the speed is too high, steps will be missed and the starting and ending points will visibly shift from the original points. One parallel port will allow the control of three stepper motors - a complete 3-D translation system.

C.2.2 Motor Control under Windows

Unfortunately, starting with Windows NT, Windows 2000 and Windows XP the parallel port cannot be accessed through the `_outp` command. A separate custom written device driver must be written for the control of the parallel port. Additionally, under all versions of Windows, multi-tasking interferes with the timing of digital pulse operations. The result is that steps are missed and accurate positioning is not possible. The solution is to run the computer in DOS mode for data acquisition and translation stage control. The hot-wire measurement setup is designed under DOS. Alternatively, in order to use Labview (a windows based data acquisition program) the stage controlling program can be run from a computer booted under DOS and the data acquisition can be run from a separate computer. Timing between the computers would be manually coordinated. Although cumbersome, such coordination has been successfully used for chemiluminescence studies. The long term solution however involves using the DIO features available on most data acquisition cards.

All multi-function data acquisition cards have the capability to perform digital input and output (DIO) operations. Additionally, these cards allow access to one or several timers. Using the DIO lines and timers it is possible to program a card to issue the appropriate stepper motor control signals. The only distinction among data acquisition cards is in the card's ability to handle a buffered digital output operation. Buffered digital output is required for the desired timing in the motor step pulses. When buffered digital output is possible, several motors can easily be simultaneously controlled. On a typical multi-function data acquisition board, eight digital lines are available for output. Assuming that each motor requires three digital lines for control (enable, direction and step), that allows only two motors to be controlled at any one time. However, under most circumstances all the motors in a translation stage will be enabled at the same time freeing up enough digital lines to control three stepper motors.

For the case where buffered digital output is not possible (as for example with some Data Translation boards) or more than three motors must be controlled, some

simple external circuitry is required. Using a quad op-amp chip along with some DIP type relay chips, n motors can be controlled by $n+2$ digital lines instead of $3n$ lines. Relays by ECE (EDR201A0500) have been used successfully. The quad op-amp is required to boost the digital signal current to close the relay. Using the digital ports, different relays can be closed at different times to control the path of the step motor control signal. The direction signal is connected to all motors at the same time. The enable signal, if required, can be connected from the relay controlling voltage or through a NOT gate. Whether or not a NOT gate is required depends on the stepper motor controller. In the case of the Applied Motion Products 2035, the NOT gate would be required as the motor is disabled when the enable input is digital high.

The step signal for the external circuitry is provided through the data acquisition board counter and timer. In general at least two timers are available on every data acquisition board. To generate a finite pulse train, the counters must be connected. First, the actual pulse issuing timer is setup for gated pulse generation. The gate signal originates from the output pin of the second timer which issues one pulse of programmed length to give the desired number of pulses. In other words, since the second timer output is connected to the first timer gate, the pulse train is only generated while the second timer output is high. Example code to set up the above described counters is provided by NI. For Data Translation boards, no code is available although the structure of the required program is exactly analogous to the NI program provided.

The LDV measurement system uses two multi-function data acquisition cards in addition to the high speed data acquisition card. In one of the experiments, the LDV system needs to control four stepper motors and so the method of connection used incorporates four relay chips and a quad op-amp as discussed above.

C.3 Stepper Motor Driver

The stepper motor driver interprets the logic signal from the computer and issues a sequence of pulses through the motor windings. The sequence depends on the

direction of motor rotation and type of connection. Stepper motor drivers used in the RFL / VACCG operate 2 phase motors. Two models of stepper motor drivers are in use. The CMD-50 (American Precision Industries) is an older model stepper motor driver that can run stepper motors requiring up to 5 A of current per phase. All stages assembled prior to the writing of this document (July 2002) use stepper motors that require large currents. Unfortunately, the CMD-50 has been discontinued. Stepper motor drivers that are capable of producing such a large current are very expensive. The CMD-50 has been replaced by the Applied Motion Products 2035 stepper motor driver. The 2035 cost is \$124 (August 2001).

The reason for the sparse availability of the high current driver lies in the difficulty of handling high currents in circuitry and the associated increased heat dissipation. In terms of performance, lower current motors can perform at the same level as higher current motors. The reason for this is that lower current motors operate at a proportionately higher voltage. The 2035 can drive motors from 0.125 A to 2.0 A at a voltage of up to about 8 V.

On both the CMD-50 and the 2035 it is the motor current that is set using a certain value resistor or slide switches respectively. The driver adjusts the voltage automatically. In setting the current it is important to realize whether or not the motor is to be connected in series or parallel. Four lead motors can only be connected in one way but six and eight lead motors can be connected in series to achieve increased torque at low speeds or in parallel for better high speed performance. For series connection, the motor current is set to 70% the rated value. Parallel connection occurs at the rated current of the motor.

Both the CMD-50 and the 2035 offer optically isolated inputs that protect the computer from damage in case the stepper motor driver burns out. For both drives, the inputs are bidirectional. As designed by the manufacturer, the user can supply a +5V supply (at least 100 mA) separate from the main stepper motor driver supply. The inputs must then be able to sink up to 15 mA of current. The inputs act as paths to ground that can either be connected or disconnected. Alternatively, the +5V supply terminal can be connected to ground (it is actually labeled COM on the

2035). In this case the current must come from the digital inputs. In the case of the 2035, this does not appear to be a problem, even though no voltage followers were installed to boost the digital output currents. In other words, the source capability of the data acquisition card is sufficient to drive the inputs. The alternative setup has not been tested with the CMD-50.

Especially for the CMD-50 proper mounting and heat dissipation is critical. All of the CMD-50's in service use an attached heat sink to prevent the driver from overheating. In the case of the 2035, less current is being handled and thus the heat flow issue is not as critical. However, the drivers should still be mounted on a smooth metal surface, able to draw away and dissipate the heat produced by the drive.

C.4 Stepper Motors

Stepper motors are defined by the following specifications:

1. Motor size (NEMA sizing convention)
2. Motor holding and running torque
3. Motor voltage and current
4. Step size and accuracy
5. Number of leads
6. Number of phases

Motor size is not important except when replacing a unit. Motor sizes are standard and replacements can usually be made easily, even with different brands. The sizing convention is called NEMA. Standard NEMA sizes start at 11 and go up to about 34 in uneven increments. The larger the number, the larger the motor. The holding and running torque of the motor is usually given in oz-in. The motor torque capabilities are related to the voltage and current requirements. The higher the voltage current product, the higher the torque capabilities. The current specification of

the motor must be compatible with the stepper motor driver. Voltage is adapted automatically to the requirements of the motor. The current however is limited by the stepper motor driver capabilities. In the case of the 2035, the limit is 2 A per phase, for the CMD-50, the limit is 5 A per phase. The voltage of the motor determines in part the specification of the power supply (see Section C.5). Each motor also has a step size specification which is usually 1.8° or 200 steps per turn. The step size is quoted with an accuracy that is usually better than 5 %.

The stepper motor drivers utilized currently in the lab only support (hybrid) 2 phase motors, where the hybrid classification is sometimes used to indicate a reversible motor. Stepper motors are further distinguished by the number of electric leads. Depending on whether the stepper motor is configured to run in series or parallel, different wires are connected. Stepper motor drivers contain documentation on how 4, 6 and 8 lead motors are to be connected. In order to be successful in the proper connection of the motor, it is imperative to obtain a wiring schematic for the stepper motor being installed. When purchasing from a surplus outlet, it is important to make sure that this information is available through the manufacturer or by matching existing working wiring configurations. Some manufacturers follow standard color coding (see the stepper motor driver manuals), but some do not.

C.5 Power Supply

In choosing a power supply for a given translation stage configuration, the motor current and voltage specifications are important. The stepper motor controllers usually accept a range of power supply voltages and then use internal regulators to actually obtain the correct voltage. Stepper motor controllers prefer unregulated power supplies, because sudden changes in current are handled better by these types of supplies. However, it is important to make sure that the unregulated power supply does not exceed the maximum input voltage when no current is being drawn from it. Under no-load conditions, unregulated power supplies can have up to 1.4 times the rated output voltage. In the case of the 2035, the maximum input voltage is 35 V

and therefore, the maximum unregulated power supply voltage should be 24 V. In any case, for the power supply voltage rating, larger is better, within the limits of the stepper motor driver. For regulated power supplies it is recommended that the power supply be rated at least five times the motor voltage rating. Additionally, the current rating of the power supply should be at least the sum of the two phase currents. The requirement can be relaxed with higher power supply voltages, since the stepper motor driver can convert a high voltage and low current into a low voltage and high current.

Multiple stepper motor controllers can be connected to the same power supply when the motors are not being used at the same time and speed performance requirements are not stringent. To get optimum speed set one stepper motor driver up with one power supply and use an unregulated power supply. Whether or not a regulated power supply is used, the positive voltage should have a slow-blow fuse to help protect the stepper motor driver.

C.6 Mechanical Connections

In order to move a translation stage, the rotational motion of the motor must be transformed to axial motion. The shaft of the motor is connected to a coupling which in general can be rigid. Backlash in the coupling should be avoided because it causes a loss of accuracy in positioning. The other end of the coupling should be connected to the machined end of a lead screw. The machined end should also pass through a bearing that will help keep the lead screw aligned with the coupling. In some of the translation stages currently in use the end of the lead screw is also bearing supported. This practice is not necessary and can result in excessive alignment difficulties. Straightness of travel is not given by the lead screw, but rather by the carriage and rail it is mounted on. The additional bearing unnecessarily makes the alignment of the lead screw and motor shaft as critical as that of the rail.

The connection between lead screw and carriage is accomplished using a flange mounted nut that rides on the lead screw. The nut has the special characteristic of

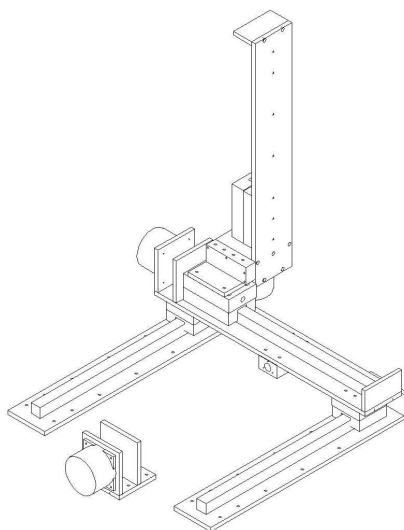


Figure C.2: CAD isometric view of 3-D traverse for LDV probe

being spring loaded to avoid backlash between the nut threads and the lead screw. The anti-backlash nut is purchased to match the lead screw threads. The traditional supplier for all the translation slide hardware including lead screws and anti-backlash nuts is Techno-Isel. Typically, Series 2 rails are purchased with either a type 1 or type 2 bearing carriages. The rails consist of two precision ground stainless steel rails mounted to tight tolerances in parallel in an aluminum rail housing. These building blocks can then be incorporated in entire traverse mechanisms. A model 3-D traverse designed for the LDV probe is shown in Figure C.2.

C.7 Supplier Contact Information

Item	Supplier	Phone	Web Address
Data Acquisition	Data Translation	(800) 525-8528	datx.com
Data Acquisition	National Instruments	(800) 258-7019	ni.com
Stepper Driver	Applied Motion Products	(800) 525-1609	applied-motion.com

Stepper Motors	C & H Sales	(626)796-2628	candhsales.com
Stepper Motors	Applied Motion Products	(800) 525-1609	applied-motion.com
Power Supply	C & H Sales	(626)796-2628	candhsales.com
Power Supply	Marlin P. Jones	(800) 652-6733	mpja.com
Power Supply	Jameco Electronics	(800) 831-4242	jameco.com
Electronic (Relays)	Jameco Electronics	(800) 831-4242	jameco.com
Hardware	Techno-Isel	(516) 328-3970	techno-isel.com

Vita

The author was born in Stuttgart Germany on June 23, 1974. At the age of three, he moved to the tiny country of Luxembourg where he stayed for the next 13 years. In 1990, he moved to Princeton, Massachusetts. He graduated from Wachusett Regional High School in 1993 and moved on to pursue a Bachelor's degree in Engineering at Virginia Tech. After beginning studies in aerospace engineering, the internship experience at MPR Associates of Alexandria, Virginia led to a change in engineering disciplines. He completed the Bachelor's degree in the department of mechanical engineering in May 1998, graduating Summa Cum Laude. He was awarded an NSF graduate fellowship to pursue a doctoral degree. Continuing a rewarding undergraduate research experience, he chose to work under Dr. Uri Vandsburger to pursue a doctoral degree in mechanical engineering, with the help of an NSF graduate fellowship. Along the way, the separate research interests of chemiluminescence and fluid mechanics allowed for an intermediate stepping stone, represented by a master's degree. In the fall of 2000, he became a United States citizen. In the fall of 2003 he married Sherrie A. Merchant. Also in the fall of 2003, he accepted a position as Advanced Propulsion Engineer with GE Global Research in Niskayuna, NY.

Permanent Address: 7 Grandview Dr.

Rensselaer NY 12144

USA