3DM-GX3®-45 Theory of Operation

MicroStrain® Little Sensors, Big Ideas®

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1. 3DM-GX3-45 Introduction

The 3DM-GX3-45 is a GPS-aided inertial navigation system (GPS/INS) consisting of an Attitude and Heading Reference Unit (AHRS), Global Positioning System (GPS) receiver, and an application processor running an Extended Kalman Filter (EKF.) The EKF is responsible for combining the output of the GPS and AHRS sensors into a single, optimal navigation solution.

The 3DM-GX3-45 has been designed to solve the problem of navigating in outdoor environments relatively close to the surface of the Earth[1]; to this end, it relies on a clear view of the sky, allowing the GPS to operate properly. Indoor and subsurface navigation, where GPS is unavailable, would require replacing the GPS sensor with a different reference system or changing the structure of the EKF to properly operate and is not in the domain of the 3DM-GX3-45. Given this, the following are likely applications for the 3DMG-GX3-45:

1) Primary navigation device in unmanned aerial, ground, and marine vehicles.
2) Manned/unmanned vehicle motion tracking and analysis.
3) Outdoor robotic systems.

The advantages of using the 3DM-GX3-45 over GPS-only and AHRS-only systems are:

1) Position, velocity, and attitude (PVA) estimation in a single, small-footprint device.
2) Reliable PVA estimation during short-duration GPS outage conditions[2].
3) An output rate of 100 Hz for high-dynamic applications.
4) PVA statistics (1-σ uncertainties) for health monitoring.
5) Bias-compensated angular rate.
6) Correlated timestamp across all 3 internal devices (Raw GPS, AHRS, EKF.)
7) Gravitational force estimation from WGS84 gravity model.
8) Magnetic to True North heading correction via WMM-2010 magnetic field modeling.

Notes:

1. The GPS used on the 3DM-GX3-45 has an altitude limitation of 50 kilometers and a speed limitation of 500 meters/second in accordance with ITAR restrictions. Please see the environmental operating limits section for additional altitude limitations if the device will be exposed to the environment.

2. GPS outage periods under 30 seconds are usually well-compensated. As the outage period extends above 30 seconds, errors in the integration of the inertial sensors compound, causing the solution to quickly diverge. Please see the example data section for the effect that different outage periods have on the accuracy of the EKF solution.

2. Detailed Device Description
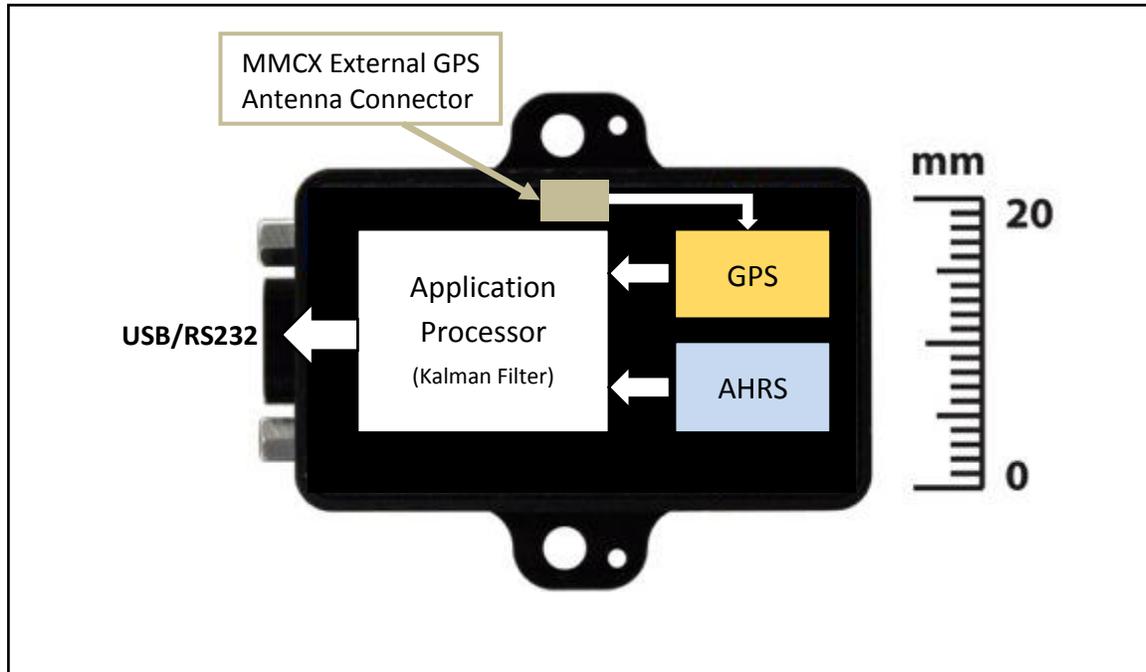
The 3DM-GX3-45 packages a miniature AHRS, GPS receiver, and application processor into a very small footprint. The AHRS circuitry is based on the 3DMG-GX3-25/35 sensor-pack design which has been tested, deployed, and validated in numerous applications worldwide. The GPS receiver is the uBlox AMY5 miniature GPS module, which provides exceptional GPS performance for its size. These two sensors communicate with the Application Processor via high-speed serial. The application processor is responsible for fusing the two data sources into a single navigation output as well as all communications with the host. A brief discussion of each of these elements follows:

An Attitude and Heading Reference System (AHRS) is a device that includes the sensors found in an Inertial Measurement Unit (IMU), combined with an algorithm to process the sensor data into a roll, pitch, and yaw/heading attitude estimate. The sensors used in an AHRS are: gyroscopes, accelerometers, and magnetometers. These sensors are arranged on the three primary axes to sense angular rate, acceleration, and the local magnetic field respectively. The gyroscopes are used to rotate the current attitude estimate when an angular rate is sensed. The accelerometers sense gravity as well as linear acceleration. The magnetometers sense the Earth's magnetic field along with local magnetic anomalies. An orthogonal set of axes can be generated from the sensed acceleration and magnetic field vectors, resulting in an estimation of the sensor's orientation in space. In an AHRS, this estimation is combined with the output of the gyroscope in either a complementary or Kalman filter to give a blended

solution. This solution represents the orientation of the device relative to the local North, East, Down (NED) frame at a particular point on the Earth's surface.

A Global Positioning System (GPS) receiver processes the signals generated by a constellation of satellites to determine its position, velocity, and the current time to a relatively high accuracy. It does this by calculating the distance (pseudorange) from a minimum of 4 satellites in known locations; thus, allowing the device to pinpoint its location based on where these ranges intersect. Because the distances are small in relation to the speed of light, the receiver must correct for its internal clock error to a very high precision, which is why 4 satellites are required instead of 3. Using its own internal Kalman filter, the GPS receiver calculates its position and velocity estimate. External aiding systems, such as WAAS in the US, help compensate for certain error sources that can affect GPS accuracy.

The application processor in the 3DM-GX3-45 is where the navigation solution is calculated, all commands are parsed and processed, and all data packets are assembled. The Kalman filter included in the 3DM-GX3-45 is suitable for a wide range of navigation applications. When a more specialized filter design is required, the architecture of the code contained on this processor allows MicroStrain engineers to conceptualize and test the new filters very rapidly. This capability is advantageous for customers with specific navigation requirements, such as wheel-speed inputs or non-GPS solutions. If you require a specific filter design due to unique requirements, please contact MicroStrain.

The 3DM-GX3-45 can communicate to the host via RS232 or USB. The device selects the appropriate connection on power-up based on which cable is connected. Please note, it is not possible to use both RS232 and USB at the same time.

3. Reference Frame Definition
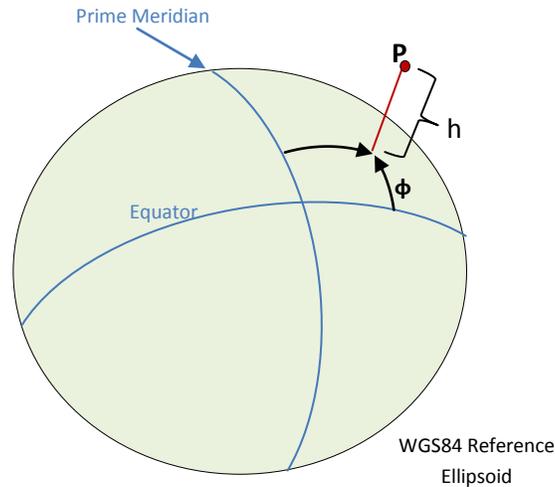
3.1 Geodetic Frame

Figure 3.1. A point on or above the Earth in the WGS84 coordinate system is given
by: latitude (φ), longitude (λ), and height above the reference ellipsoid (h).

The World Geodetic System is the standard for cartography and navigation; the latest revision, WGS84, is the reference coordinate system for GPS. The WGS coordinates are latitude (φ), longitude (λ), and height (h) above the reference ellipsoid. Latitude ranges from -90 degrees at the South Pole to 90 degrees at the North Pole. Longitude ranges from -180 to 180 degrees, with 0 degrees being the prime meridian. The -180/180 degree switchover occurs in the middle of the Pacific Ocean and includes a section of the International Date Line. The model takes into account the oblateness of the Earth's surface.

The 3DM-GX3-45 reports position using this coordinate frame. It also calculates the magnitude of the local gravity vector using the WGS84 reference formulas.

3.2 North East Down (NED) Frame

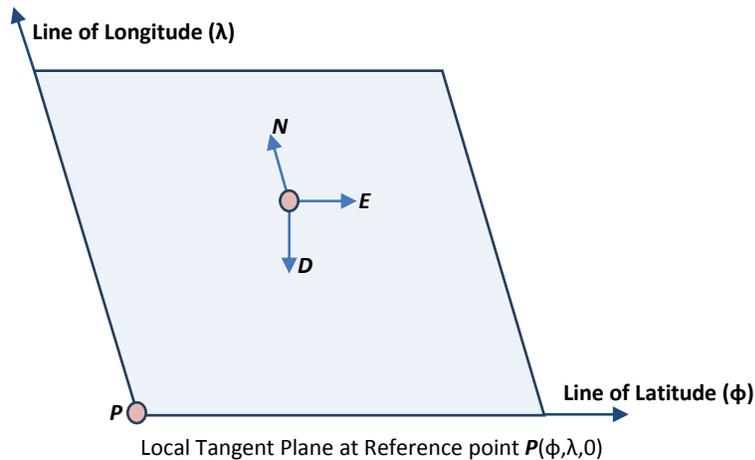Local Tangent Plane at Reference point $P(\phi,\lambda,0)$

Figure 3.2. The NED frame is constructed with the North vector pointed along the line of longitude, the East vector along the line of latitude, and the Down vector normal to and towards the tangent plane.

The NED frame is a local coordinate frame which is formed by a tangent plane located at a particular point on the WGS84 reference ellipse; specifically, the current coordinates. The unit vectors lay along true north, parallel to longitude; true east, parallel to latitude; and down, normal to the plane. The assumption when using the NED frame is that the local surface can be reasonably approximated by a flat plane. For most applications, this assumption is valid and provides a more intuitive reference frame for expressing velocity and attitude information than a global frame.

The 3DM-GX3-45 reports velocity in this frame and attitude with respect to this frame.

3.3 Sensor Frame

Figure 3.3. The sensor frame is marked on the lower right corner of the package.
The z axis points down through the bottom of the device.

The sensor frame is indicated on the top of the device and is oriented such that the unit vectors are as follows: x parallel and outward from the connector; z normal to the top and running from top through the bottom; the y axis completes the frame using the right hand rule. These axes were selected so that when the connector on the device is pointed true north and the device is upright and level, the sensor frame will match the NED frame exactly, giving zero rotation (when represented by Euler angles.)

The 3DM-GX3-45 reports acceleration, angular rate, delta theta, delta velocity, and sensor biases in this frame.
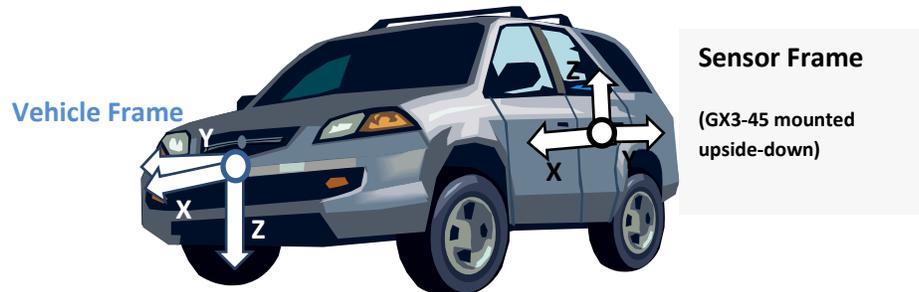
3.4 Vehicle Frame

Figure 3.4. In this example, the user has defined the vehicle frame to be located at the front bumper of the SUV. The orientation of the vehicle frame is always X-axis pointed forward, the Z-axis pointed down, and the Y-axis pointed towards the passenger side. The sensor is mounted in the rear of the vehicle 2 meters aft of the new vehicle frame. The user has mounted with its X-axis co-aligned with the vehicle frame X-axis, but upside down with-respect-to the vehicle frame. The proper transformation would be: 180 degrees roll, 0 degrees pitch, and 0 degrees yaw. The offset (assuming no Y or Z component) would be: [+2, 0, 0] meters.**hλ**

The 3DM-GX3-45 includes the option to define a transformation and offset, from the sensor frame to the vehicle frame. This transformation is most useful when, for some reason, the sensor cannot be mounted in the same location and with the same orientation as the vehicle frame. The vehicle frame is always defined as: X-axis pointed forward, Z-axis down, and Y-axis completing the right-hand rule (also known as aircraft coordinates.) The transformation from sensor to vehicle frame is defined with Euler angles and is expressed as a rotation ***from the sensor frame to the vehicle frame***. The offset is the vector location of **the *origin of the vehicle reference frame with respect to the origin of the sensor frame, expressed in the sensor frame***.

In the 3DM-GX3-45, the transformation affects the following quantities: Estimated Orientation, Estimated LLH Position, Estimated Linear Acceleration, Estimated Angular Rate, and the Estimated Gravity Vector.

The offset affects the following quantities: Estimated LLH position.

Please note: AHRS dataset quantities are always expressed in the sensor frame and are unaffected by this transformation, only NAV dataset quantities are affected. Additionally, the transformed acceleration is expressed at the location of the sensor but in the new frame of the vehicle; thus, if the sensor is offset from the CG and the vehicle is undergoing a rotation, an acceleration (in addition to any linear acceleration of the CG) will be sensed in accordance with (tangent acceleration) = (angular rate)*(distance from CG). Please see the 3DM-GX3-45 Data Communications Protocol (DCP) for the definition of the various available AHRS, GPS, and NAV dataset quantities.

4. Kalman Filter Description

The 3DM-GX3-45 combines the information from a GPS receiver and an AHRS sensor to calculate a navigation solution that incorporates the strengths of these individual systems while minimizing their weaknesses. A discussion of the limitations of each of the sensors individually follows:

The GPS solution is bounded and typically very good, but it is susceptible to several error sources. Due to the geometry of the satellite constellation, vertical position accuracy is typically less than horizontal position accuracy. Additionally, errors from atmospheric and multipath effects, as well as clock error further degrade the accuracy of the solution. Arguably, the largest problem with a GPS-only solution for navigation is that a single GPS receiver cannot give you the orientation of the vehicle/device unless the device coordinate frame is co-aligned with the vehicles velocity vector. For a lot of applications, this assumption is too restrictive. For example, the pitch of an aircraft typically does not match the angle the velocity vector makes with the horizon. This occurs because the aircraft's wings must be at an angle with the oncoming air to generate lift. Making the assumption that the two values were the same and using the pitch angle as an input to an autopilot would be a mistake. In order to obtain the attitude of the vehicle, something more is needed.

An Attitude and Heading Reference System (AHRS) is a device capable of providing the user the attitude of the vehicle. Although these devices can be quite good, several sources of error exist in a conventional AHRS attitude estimate. First, the algorithm assumes the acceleration vector is dominated by Earth's gravity, with only transient linear accelerations. When long-duration linear accelerations are experienced, such as when an aircraft performs a sustained 2G turn, the AHRS will report incorrect pitch and roll angles. This error is the direct result of the assumption that the accelerometers are only sensing Earth's gravity. A second source of error occurs when the device attempts to measure the Earth's magnetic field. This field is very weak compared to the numerous magnetic anomalies typically found in vehicles and close to the Earth's surface. If the magnetic anomalies in the vehicle remain constant with respect to the sensor, i.e. no translation or rotation between the two, they can be compensated for by performing a hard iron and/or soft iron calibration. The hard iron calibration compensates for magnetic sources close to the sensor and the soft iron calibration compensates for ferromagnetic objects, which distort magnetic field lines. Non-constant and external sources, such as those found when travelling through cities, cannot be compensated and may cause large errors in the heading estimation. Transient errors can be suppressed when the magnetometer readings are combined with information from the gyroscopes, but only for periods on the order of a few seconds. Longer duration anomalies will result in heading errors. A third source of error occurs when attempting to navigate between geographic waypoints expressed in latitude and longitude. This error is due to the difference between detecting magnetic north, which is output by the AHRS sensor, and true north, which is used to define lines of longitude. If the AHRS is always used in one geographical location, the user can correct for this difference using a constant offset. If the AHRS is used over a wide range of longitude, the magnetic declination must be calculated from a magnetic model or obtained from GPS subsystem which outputs

this data. The greatest problem with an AHRS is that it is an attitude-only device and requires a GPS for position and velocity.

As a first attempt at an improved navigation solution, a user could get position and velocity from a GPS receiver and attitude from an AHRS. This is an acceptable solution for many navigation problems, but is susceptible to most of the errors described above. A more accurate estimation of position, velocity, and attitude can be found by fusing the data from these two independent systems using a Kalman filter.

The 3DM-GX3-45 runs a loosely-coupled Extended Kalman Filter. In a loosely-coupled filter, the inertial sensors in the AHRS are used to propagate the state estimation at a high rate (100 Hz); whereas, the GPS position and velocity measurements are used to periodically correct the state (4 Hz.) This form of Kalman filter is called a sensor fusion filter as it is combining similar information from multiple sources in a complementary way. This combination takes into account the statistical properties of the sensors used, providing a better estimate of the true state than either system individually. The 3DM-GX3-45 has a full-state dynamics model, thus the state propagation utilizes Newton's and Euler's equations of motion with the acceleration and angular rate treated as control inputs.

In addition to the GPS measurement, the AHRS magnetometer is available to correct heading misalignments which occur during periods of low dynamics. The magnetometer corrections can be disabled for applications where large, non-constant magnetic interference sources exist, which would impair their use (e.g. mounting the 3DM-GX3-45 on a gimbal close to the frame of a ground vehicle.)

As stated previously, the Kalman filter estimates the full states of position, velocity, and attitude. In fact, the filter estimates 13 states: 3 position, 3 velocity, 4 attitude (as a quaternion), and 3 gyro bias states. The bias states are estimated in order to compensate for the time-varying biases inherent in MEMS inertial sensors, which are the largest error sources for these devices. The bias states are subtracted from the gyro inputs, thus providing more accurate inertial data to the propagation stage of the filter. This enhances overall accuracy and is especially useful during GPS outage conditions.

The Kalman filter also provides statistical information about the quality of the estimated states described in a covariance matrix. The diagonal terms of the matrix are the variance of each state, thus the square root of these values are 1-sigma standard deviations. These values give the filter's estimation of how well it "knows" the individual states, given what it "knows" about the statistical properties of the noise sources of the various sensors. The GPS position and velocity noise are not white, but are treated as such in a loosely-coupled filter. This approximation results in a less-than-optimal filter, but the advantages of this type of filter outweigh this sub-optimality.

5. Real-Time Operation

5.1 Device Configuration Considerations

5.1.1 Bandwidth

Users should be cautious about bandwidth limitations when using RS232. Most personal computers limit RS232 communications to 115,200 baud even though the 3DM-GX3-45 is capable of speeds up to 921,600. At lower baudrates, the available bandwidth can be consumed rather quickly. This happens because of the large number of data fields the typical user desires and the high data rates available (100 Hz.) Data rate decimation for the required data fields should be selected with care and are described in the 3DM-GX3-45 Data Communications Protocol (DCP.) Severely overrunning the communication bandwidth can have adverse effects on the filter performance due to excessive CPU usage.

5.1.2 GPS Antenna Offset Effects

For the best possible position accuracy, the GPS antenna offset should be defined to the highest degree possible, preferably down to the cm or mm range. Additionally, the user should strive to minimize this distance as large offsets (10s of meters or more) will result in position oscillation due to small orientation inaccuracies. For instance, a 1 degree error in attitude with a 10 meter antenna offset would result in a position error of approximately 0.17 meters; whereas, if the offset was only 1 meter, the position error would be 1.7 cm.

5.1.3 Sensor to Vehicle Frame Transformation and Offset Effects

The same logic that was applied to the GPS antenna offset can be applied to the sensor to vehicle frame offset. The transformation from the device coordinate frame to the vehicle coordinate frame should be defined to the highest angular accuracy possible. The easiest way to accomplish this is to co-align the frames. If this is not possible, using a simple transformation, such as 90 or 180 degree rotations on a single axis are preferred. For complex transformations between the frames, a calibration should be performed or analysis from a solid model should be conducted.

5.2 Filter Considerations

5.2.1 Initial Convergence

After a successful initialization, a period of convergence for the Kalman filter states occurs. Position, velocity, roll angle, and pitch angle typically converge very quickly. Heading, accelerometer bias, and gyro bias will take more time to converge. If the initial attitude estimate provided to the filter is well outside of the true attitude, the filter may diverge and never recover. This is most likely to occur for the heading estimate when a poor value is used for initialization and when the vibration environment is strong. Should this occur, it is recommended that the filter is reset and a new attitude estimate is

provided. Please see the 3DM-GX3-45 Data Communications Protocol (DCP) for the various ways of providing an initial attitude estimate.

5.2.2 Bias Convergence

Accurate estimation of the biases can take several minutes to converge; therefore, after the filter is initialized, the free-inertial performance will continue to improve until the bias estimations settles. The MEMS sensor manufacturers quote bias drift stability numbers which correspond to the expected drift in bias while the sensor is operating. The filter attempts to track the changing biases over time and a user can expect these bias estimates will be non-constant during a navigation run.

5.2.3 Heading Drift and Heading Sensor Use

The estimated heading will drift when the device is stationary or moving at a constant velocity if no heading sensor is enabled. This occurs because no assumption has been made as to how the device is mounted in the application; instead, the only mechanism to correct for heading errors when heading updates are disabled is sufficiently large changes in velocity (acceleration) experienced by the device. If heading drift is experienced in your application, it is recommended that you either turn the magnetometer compensation on, use the GPS heading information if appropriate, provide an external heading source, or move the vehicle in a dynamic way to assist the filter in recapturing the heading (e.g. slight S-turns in an aircraft which has been travelling in a straight line for an extended period of time.)

5.2.4 Solution Uncertainty Monitoring

The 3DM-GX3-45 navigation data set includes a filter status field that contains a set of covariance status flags. These flags pertain to high covariance values for position, velocity, and attitude. The user should monitor these flags and cross-check against the corresponding uncertainty fields when they are asserted. This can assist the user in determining if they should trust the solution generated by the Kalman filter. When the filter is first initialized, it is likely that some of these values will be beyond limits and the flags may be asserted; this fact should be taken into account when developing automated monitoring systems.

5.2.5 Vehicle Dynamics Modes

The vehicle dynamics mode setting adjusts the GPS Kalman filter's expectation of the vehicle's motion. By doing this, the filter is better able to account for the effects that different dynamic regimes have on changes in satellite pseudoranges. Each regime - portable, automotive, and airborne have different velocity and altitude limitations. Please see the 3DM-GX3-45 Data Communications Protocol (DCP) for more description on these settings.

6. Operating Limitation

GPS Outage Limitations

GPS outages should be kept to a minimum. The filter will continue to provide relatively good position, velocity, and attitude estimations during outages of 30 seconds or less. Position and velocity errors will grow exponentially with measured acceleration error, and attitude errors will grow linearly with estimated bias error. Please monitor the 1-sigma uncertainties during GPS outage conditions.

Angular Rate and Acceleration Limitations

The 3DM-GX3-45 angular rate and acceleration range depend on the sensors installed in the device. Please check the product description for your particular device for these ranges. Exceeding the specified range for either sensor will have an adverse effect on the accuracy of the Kalman filter solution. Please select the proper sensors for your application and, if you are unsure what the appropriate range is, contact Microstrain for assistance.

Vibration Isolation

The 3DM-GX3-45 should be isolated from strong vibrations a much as possible. Strong, continuous vibrations appear as unaccounted noise to the filter, degrading its performance. If you feel that you are experiencing poor performance due to vibration issues, attempt to isolate the vibration frequencies or contact MicroStrain support.