TECHNICAL NOTE

REFERENCE FRAME ROTATION

Calculating & Configuring Platform Frame

VECTORNAV

1 INTRODUCTION

The goal of this technical note is to describe how to utilize the Reference Frame Rotation register used by VectorNav sensors. This note relies on concepts and math behind rotation and attitude representation. For more information on these topics, refer to the *Attitude Representations* section of the VectorNav Inertial Navigation Primer.

The Reference Frame Rotation register (Register 26) allows the sensor to output the attitude—and other available measurements such as the velocity, acceleration, and angular rate—of a body rigidly attached to the sensor rather than the sensor's internal reference frame. This can be useful for system-level consistency or ease of data interpretation. Entering a reference frame rotation (RFR) will not have an impact on either the initialization time or the sensor's performance.

> On VN-2XX and VN-3XX products, the following configuration registers will be impacted by a reference frame rotation:
> - GNSS Internal A Antenna Offset register (Register 57)
> - External GNSS Antenna Offset register (Register 157)
> - INS Reference Point Offset register (Register 105)
> - GNSS Compass Antenna Baseline register (Register 93) (VN-3XX products only)
>
> If an RFR is configured in Register 26, the measurements in these registers must be specified in the body-frame. For more information on each of these registers, refer to the sensor's Interface Control Document.

2 VECTORNAV REFERENCE FRAMES

Any reference frame, or coordinate system, can be defined by an origin that defines a position in space and three orthogonal unit vectors—or axes—that make up a right-handed system. Any vector in three-dimensional space can be described in any reference frame by projecting the vector onto the desired reference frame. The projections on the reference frame axes are the components of the vector.

This section discusses the VectorNav sensor-frame and body-frame in detail. The specific reference frame in which a vector is described is denoted by its superscript. For example, an acceleration vector described in the sensor-frame is denoted as ${}^{\mathcal{S}}a$, where described in the body-frame it is denoted as ${}^{\mathcal{B}}a$. Throughout this technical note, all reference frames share an origin, but differ in their orientations.

The attitude of a reference frame can be represented by several parameter systems, including the Euler angles and the Euler parameters (quaternion). The Euler angles (yaw-pitch-roll) are the most commonly used forms of the attitude parameters and are used on all VectorNav products to describe the attitude of the sensor reference frame relative to the North-East-Down (NED) frame through three consecutive rotation angles $(\psi - \theta - \phi)$. The order of the rotation axes is important, as performing the rotations in an alternate order computes a different reference frame.

2.1 Sensor Reference Frame

All VectorNav sensors use a right-handed reference frame. The sensor reference frame on all VectorNav products is aligned as shown in Figure 1. The x-axis points forward, the y-axis points rightward, and the z-axis points downward. A yaw angle is defined as a rotation about the z-axis; a pitch angle is defined as a rotation about the y-axis; a roll angle is defined as a rotation about the x-axis. The sensor-frame is shown on the top of the sensor's aluminum casing.

2.2 Body Reference Frame

In many cases, the user may want to read the sensor output values in an arbitrary reference frame—called a body-frame—due to mechanical offsets, a mounting misalignment, or system-level integration. The body-frame is often aligned to the mounting platform, vehicle, aircraft, camera, LiDAR sensor, external INS, or any other body rigidly attached to the sensor. It may be rotated any amount relative to the sensor-frame using a reference frame rotation (RFR) which can be applied via the Reference Frame Rotation register (Register 26). This technical note refers to the rotation matrix in the Reference Frame Rotation register as the sensor-to-body rotation matrix.

Sensor Reference Frame

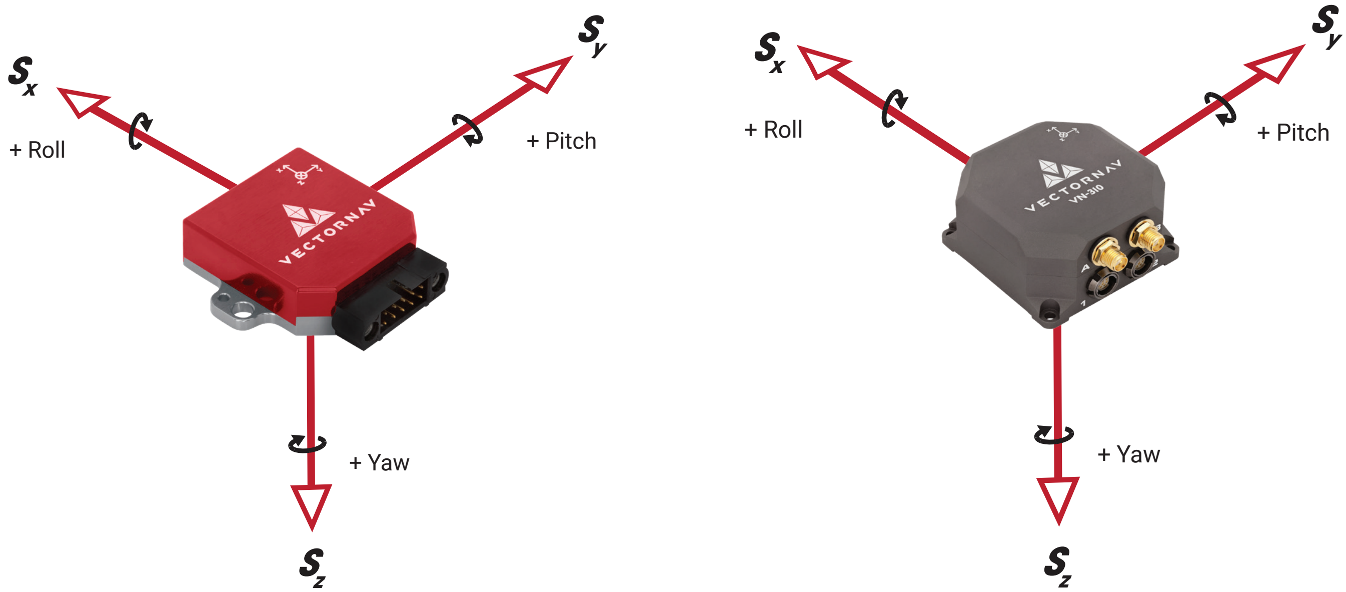


FIGURE 1

2.3 Using the Reference Frame Rotation Register

The sensor-to-body rotation matrix can be configured via Register 26 on all VectorNav sensors. The parameters for the register are defined in Eq. 1 and Figure 2. Because this sensor-to-body rotation matrix affects measurements used in the internal Kalman filter, these settings must be saved to the non-volatile memory and then the sensor must be reset before any changes will take effect.

$$
{}^{\mathcal{B}}\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{bmatrix} RFR00 & RFR01 & RFR02 \\ RFR10 & RFR11 & RFR12 \\ RFR20 & RFR21 & RFR22 \end{bmatrix}^{\mathcal{S}} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} \tag{1}
$$

Reference Frame Rotation Register

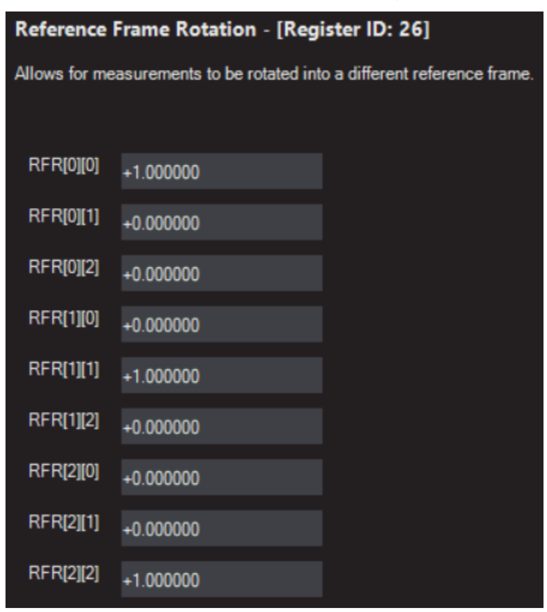
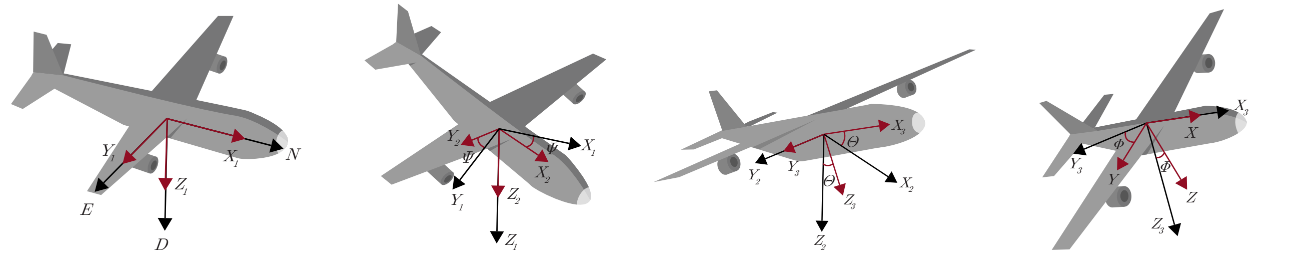


FIGURE 2

3 ROTATION OF REFERENCE FRAMES

A sequence of Euler angle rotations is used to transform the components of a vector ${}^{\mathcal{S}}\boldsymbol{v}$ from the sensor-frame to the body-frame ${}^{\mathcal{B}}\boldsymbol{v}$. Figure 3 illustrates the consecutive Euler angle rotations using the standard yaw-pitch-roll $(\psi - \theta - \phi)$ angles, which is also defined as the (3-2-1) Euler angle rotation.

Sequence of Yaw-Pitch-Roll Rotations



(a) Original Sensor-Frame (b) Yaw Rotation (c) Pitch Rotation (d) Roll Rotation

FIGURE 3

The three independent rotations can be merged through an ordered matrix multiplication to produce

$$\begin{aligned}
{}^{\mathcal{B}}\boldsymbol{v} &= R_1(\phi)R_2(\theta)R_3(\psi)\,{}^{\mathcal{S}}\boldsymbol{v} \\
&= \begin{bmatrix} c(\theta)c(\psi) & c(\theta)s(\psi) & -s(\theta) \\ -c(\phi)s(\psi)+s(\phi)s(\theta)c(\psi) & c(\phi)c(\psi)+s(\phi)s(\theta)s(\psi) & s(\phi)c(\theta) \\ s(\phi)s(\psi)+c(\phi)s(\theta)c(\psi) & -s(\phi)c(\psi)+c(\phi)s(\theta)s(\psi) & c(\phi)c(\theta) \end{bmatrix} {}^{\mathcal{S}}\boldsymbol{v} = R(\psi,\theta,\phi)\,{}^{\mathcal{S}}\boldsymbol{v},
\end{aligned} \tag{2}$$

where the trigonometric functions $(c = cos)$ and $(s = sin)$. Eq. 2 is specific to the order in which the rotations are performed, and a derivation can be found in the VectorNav Inertial Navigation Primer.

A sensor-to-body rotation matrix is often calculated by multiplying together two partial rotation matrices: the coarse alignment rotation and the fine alignment rotation, as shown in Eq. 3. This section discusses these two partial rotation matrices in detail.

$$RFR = R_{\text{Fine}} R_{\text{Coarse}} \tag{3}$$

In cases where fine alignment is not necessary or where it cannot be calculated, the sensor-to-body rotation matrix is simply the coarse alignment rotation matrix.

3.1 Coarse Alignment Rotation

The coarse alignment rotation captures large offsets between the sensor and body reference frames. Its angles are often determined during the design phase from CAD software, a mechanical drawing, or from manual inspection.

In many instances, the sensor-frame is closely orthogonal—some 90° rotation—to the body-frame. For such cases, the coarse alignment rotation matrix will only contain -1, 0, and +1 as the only required operation is a direct axis-to-axis remapping. Each row and column of the coarse rotation matrix will contain either exactly one +1 or exactly one -1.

3.2 Fine Alignment Rotation

Once the coarse alignment rotation has been applied, the fine alignment rotation can be used to capture any remaining small offsets, such as from mounting misalignment. While the coarse rotation is often determined during the design stage of a product, the fine rotation is calculated on a part-by-part basis after final assembly of the product. It most commonly captures mounting error offsets on the order of fractions of degrees. The fine alignment rotation is not as widely used as the coarse alignment rotation because it has a much more minor effect and can be laborious and difficult to calculate.

Determining Fine Alignment Matrix Values

There are many ways to determine the fine alignment matrix values depending on the application, type of motion possible, and the kind of measurements that can be obtained. Calculating a fine alignment rotation matrix typically requires at least two reference vectors of some type that are ideally orthogonal. The most common reference vector used for such calibration is the gravity vector which is compared against accelerometer measurements from the sensor in a series of static orientations. Generally, this fine alignment is done through a dedicated calibration performed either offline or in-situ.

Throughout the calibration process, errors from measurement noise and sensor bias must be considered. To eliminate sensor noise as an error source, it is recommended that each sample be a simple average over at least a ten-second window; if the sensor is in a vibratory environment, more time will be necessary. While time averaging reduces noise in the calibration process, error can also be introduced through bias. The biases must be calibrated either before beginning or as a part of the fine alignment calibration, which typically requires the user to sample additional orientations. When calibrating accelerometer biases, the best practice is to sample at least six orientations across a full 360° rotation about each axis, known as a tumble test. Thermal transients can also affect the sensor bias, so it is recommended that the sensor be at steady-state temperature during the calibration process.

As discussed in Section 2.2, the body-frame can represent either a mechanical body—such as a vehicle or mounting platform—or an external sensor's reference frame—such as a camera axis or another INS. These two categories may be approached differently. The following methods detail various offline calibrations that can be performed to obtain the data required for use in the Fine Alignment Matrix Calculator, described in Section 4.3. If the following calibration procedures are not feasible in your application, contact VectorNav Support for additional assistance.

Reference 1: Physical Body Alignment In cases where the body-frame represents a physical body, the most common practice is to collect data using a dedicated test fixture. Such a fixture often consists of a calibrated cube or multi-axis turntable. The jig is then placed on a level surface and the sensor is sampled when the jig is rotated to each of its six faces. To ease calculations, one of these orientations is often defined as level. This type of calibration procedure is ideal for hand-held applications or small systems.

When the body is too large to be placed in a dedicated test fixture or is too cumbersome to be fully rotated about each axis, an external orientation measurement can instead be used. The body should be placed in as wide of an orientational range as is possible, while the angle of the body is recorded from an external source at each static orientation alongside the sensor's accelerometer measurements.

Reference 2: External Sensor Alignment If the body-frame represents the reference frame of an external sensor, a separate test fixture is often not necessary as the external sensor can directly produce reference vectors for calibration. The rigid body is placed in a series of orientations spanning the full operational range. At each orientation, accelerometer measurements are collected from the VectorNav sensor alongside attitude values from the external sensor. From this data, it is possible to construct a full fine alignment matrix, along with bias values for the VectorNav sensor. Since this process aligns the inertial sensor directly to reference vectors produced by the external sensor, it is often the most precise calibration possible.

One special case in this category includes sensors which do not output a full attitude, but can limit movement to rotation about a single axis, such as a gimballed camera. By sampling a full 360° range about that axis, the VectorNav sensor can be fully calibrated using only the reference rotation angle. This allows the VectorNav sensor to align with high precision about that axis.

4 VECTORNAV TOOLS

VectorNav offers three tools to calculate and apply the sensor-to-body rotation matrix. The first two are available in VectorNav's Control Center software while the third tool is available as an embedded library. After using these tools to calculate and configure the RFR, the user must write the settings to non-volatile memory using the Write Settings command for the RFR to persist through a power cycle. The sensor must then be reset in order for the RFR to take effect.

4.1 Simple Reference Frame Calculator

The Simple Reference Frame Calculator is a tool within Control Center, as seen in Figure 4, that calculates and applies an orthogonal rotation matrix. Using this tool will reset the values back to factory default before applying the newly-calculated matrix, losing any calibration changes currently stored in the Reference Frame Rotation register (Register 26). This will occur whether the existing register values are from manual entry, a previous use of the Simple

Reference Frame Calculator, or the Advanced Reference Frame Calculator. Consequently, if a user wishes to apply a coarse matrix from the Simple Reference Frame Calculator and a fine matrix from the Advanced Reference Frame Calculator, the Simple Reference Frame Calculator must be used first.

Simple Reference Frame Calculator Location

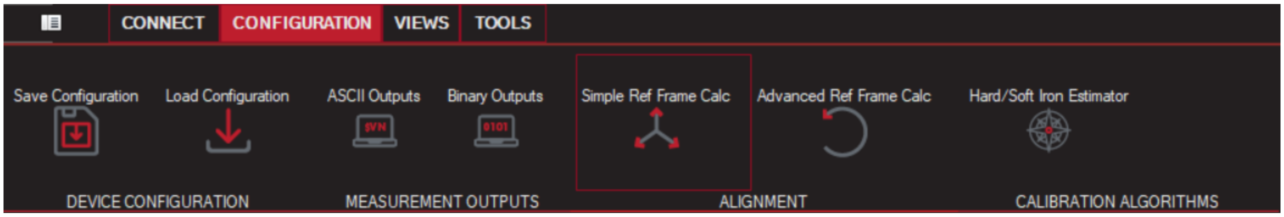
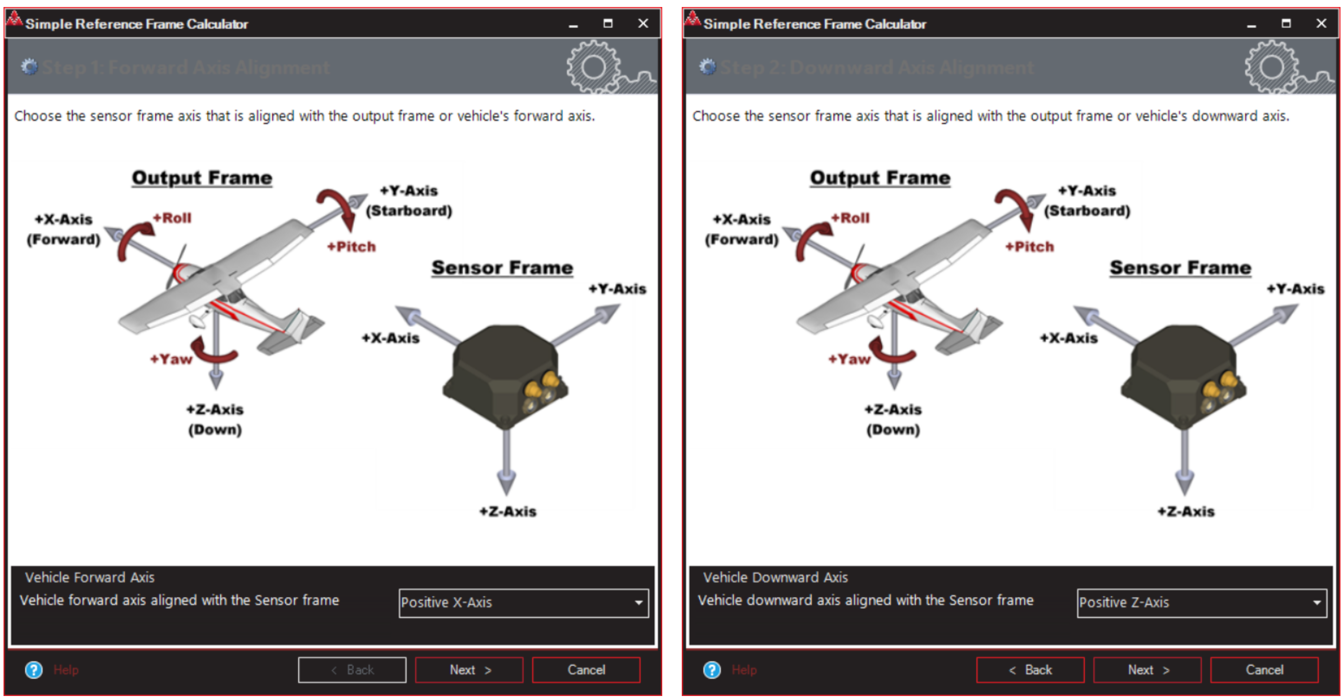


FIGURE 4

The tool has two prompts: one to select which sensor axis align with the body's forward axis (shown in Figure 5a) and a second to select which axis aligned with the body's down axes (shown in Figure 5b). Following these, there is a prompt to write the settings and reset the sensor—the user must press *Yes* before any changes will be applied.

Simple Reference Frame Calculator



(a) Step 1 (b) Step 2

FIGURE 5

4.2 Advanced Reference Frame Calculator

The Advanced Reference Frame Calculator is a tool within Control Center, shown in Figure 6, that calculates and applies a rotation matrix based on any Euler angle rotation sequence. It is most useful either for applying non-orthogonal coarse rotations or for applying fine alignment rotations. Differing from the Simple Reference Frame Rotation Calculator, the rotations from the Advanced Reference Frame Rotation Calculator are additive to the current value in the Reference Frame Rotation register—they are applied on top of any coarse or fine alignment rotations already applied. Consequently, it is possible to progressively fine-tune the sensor-to-body rotation matrix by entering small values until the desired sensor outputs are achieved.

As shown in Figure 7, this tool only requires three user-input rotation angles. Using the default ZYX rotation order, Rotations 1, 2, and 3 correspond to yaw, pitch, and roll, respectively. The values represent the rotation about the current sensor axis necessary to achieve the desired sensor axes—that is, if the current sensor x-axis points North-East and the body x-axis points North, the user should enter [−45°, 0°, 0°] into the tool.

Advanced Reference Frame Calculator Tool Location

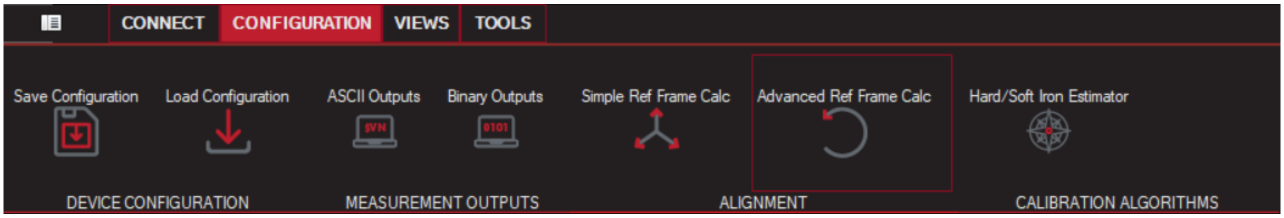


FIGURE 6

Advanced Reference Frame Calculator Tool

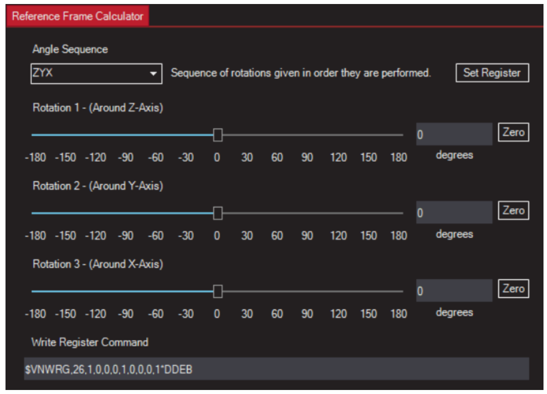


FIGURE 7

If using this tool to calibrate the sensor's pitch/roll misalignment, the negated value of the current pitch/roll (assuming a small angle offset) should be input into the tool. This process can be repeated until the sensor reports a pitch/roll of zero.

4.3 Fine Alignment Matrix Calculator

The Fine Alignment Matrix Calculator is a C-code algorithm that calculates the fine alignment rotation matrix, accelerometer bias, and gyroscope bias based on sensor data and corresponding body orientation values. The user passes a series of static accelerometer and gyroscope measurements as well as the body's pitch and roll as measured by an external source into the tool which then returns the 3-axis accelerometer bias, 3-axis gyroscope bias, and the fine alignment rotation matrix. This Fine Alignment Matrix Calculator is available royalty-free to VectorNav customers; please contact VectorNav Support to request this software.

5 REFERENCE FRAME ROTATION EXAMPLES

In order to better understand how to calculate and apply a reference frame rotation onto a VectorNav sensor, the examples below walk through calculating and applying a simple coarse alignment rotation via manual entry as well as through the Simple Reference Frame Calculator tool. Building on the coarse alignment rotation examples, the final example details how to apply a fine alignment rotation using the Advanced Reference Frame Calculator.

5.1 Coarse Alignment Through Manual Entry

Figure 8 shows an example of a simple reference frame rotation from the sensor-frame to the user-defined body-frame. From Figure 8, it can be observed that S_x is aligned with negative B_x, S_y is aligned with negative B_y, and finally S_z and B_z are in the same direction. A simple orthogonal rotation will properly align the sensor-frame to the body-frame.

By inspection, the necessary rotation is 180° about the S_z axis. The sensor-to-body rotation matrix can be calculated using Eq. (2) by setting the ϕ and θ angles to zeros and applying only a yaw rotation of 180° as:

$$
\begin{aligned}
RFR &= R_1(0)R_2(0)R_3(180) \\
&= \begin{bmatrix} c(0)c(180) & c(0)s(180) & -s(0) \\ -c(0)s(180)+s(0)s(0)c(0) & c(180)c(0)+s(0)s(0)s(180) & s(0)c(0) \\ s(0)s(180)+c(0)s(0)c(180) & -s(0)c(180)+c(0)s(0)s(180) & c(0)c(0) \end{bmatrix} \\
&= \begin{bmatrix} cos(180) & sin(180) & 0 \\ -sin(180) & cos(180) & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\end{aligned}
$$

Sensor-Frame and the User-Defined Body-Frame

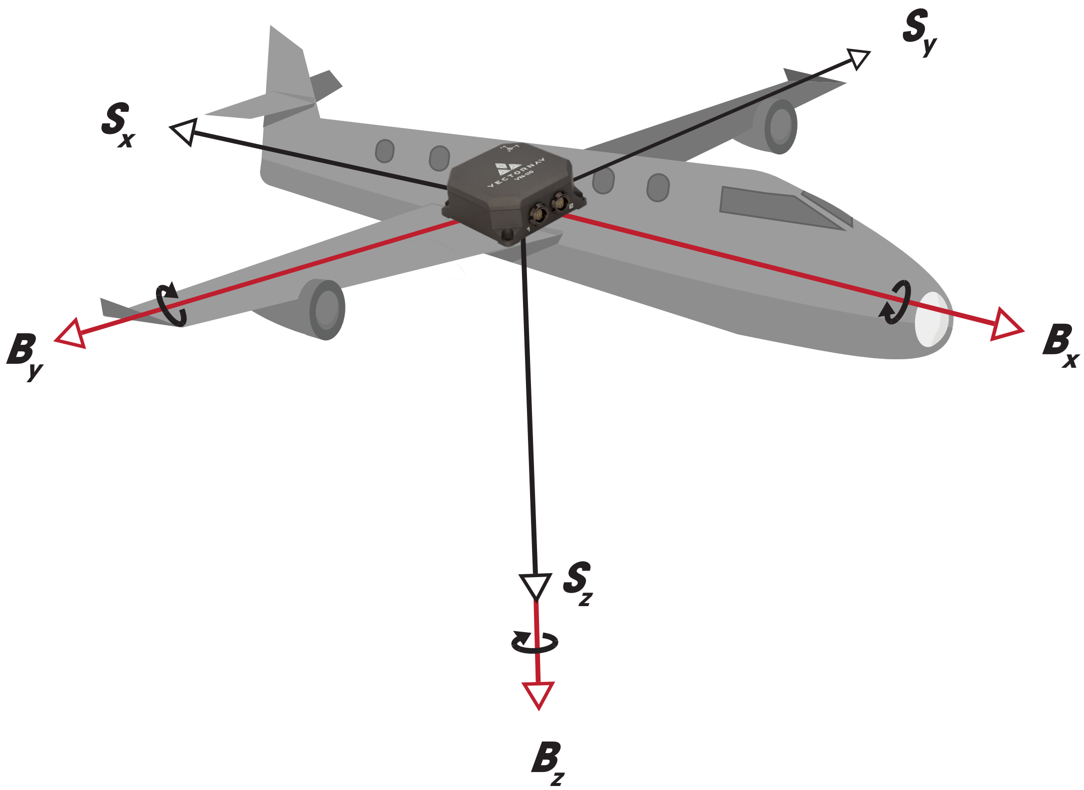


FIGURE 8

This RFR can be transmitted to the sensor using two different techniques (detailed in Section 2.3):

- Using Control Center, under the Config Registers IMU subsystem, change the sensor-to-body rotation matrix with the above-calculated RFR matrix and then issue a Write Settings command to save the values to the sensor's non-volatile memory.
- Send the command `$VNWRG,26,-1,0,0,0,-1,0,0,0,1*1FB9` to write the register using a terminal tool (such as the Terminal window in Control Center) and then issue a Write Settings command using `$VNWNV*57`.

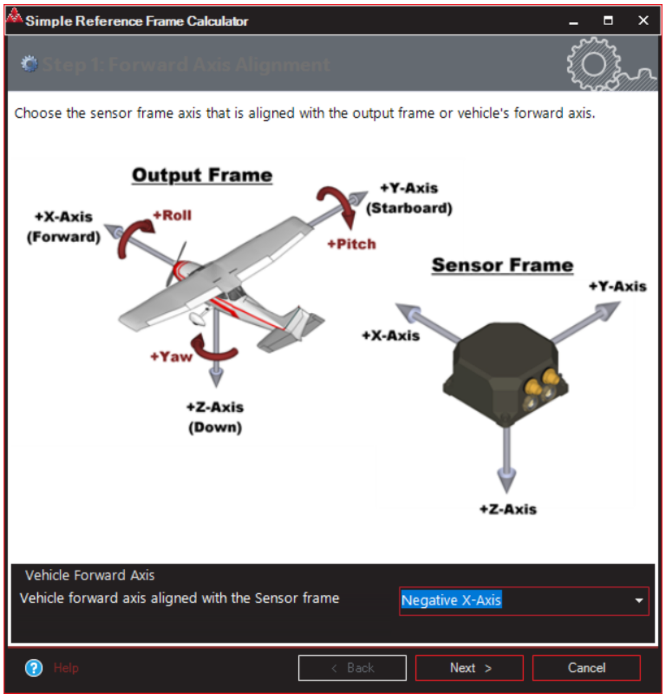
Using either method, the sensor must be reset before changes will take effect.

5.2 Coarse Alignment Through Simple Reference Frame Calculator

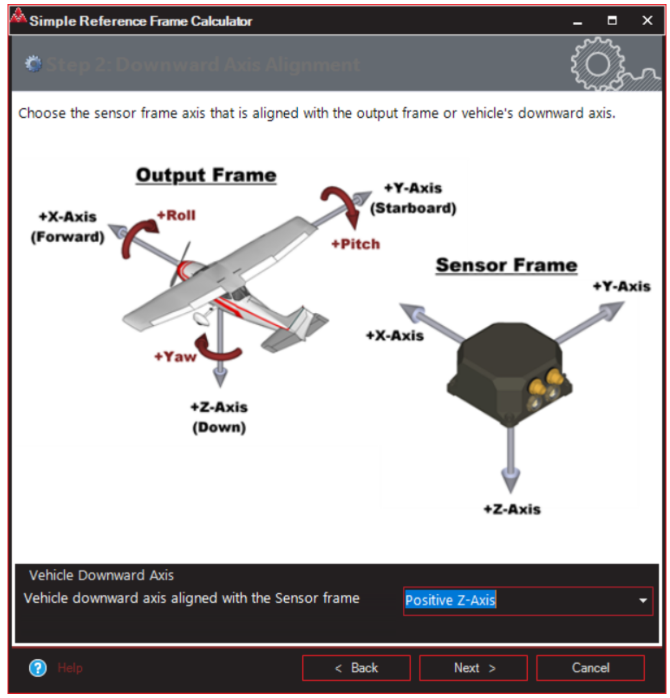
This is an identical example as shown in Section 5.1, except it is completed using the Simple Reference Frame Calculator, following methodology described in Section 4.1. To do so:

1. Connect to the sensor via VectorNav's Control Center software and open the Simple Reference Frame Calculator.
2. Select which axis of the sensor aligns with the forward axis of the body (in this case the negative x-axis) as shown in Figure 9a and click *Next*.

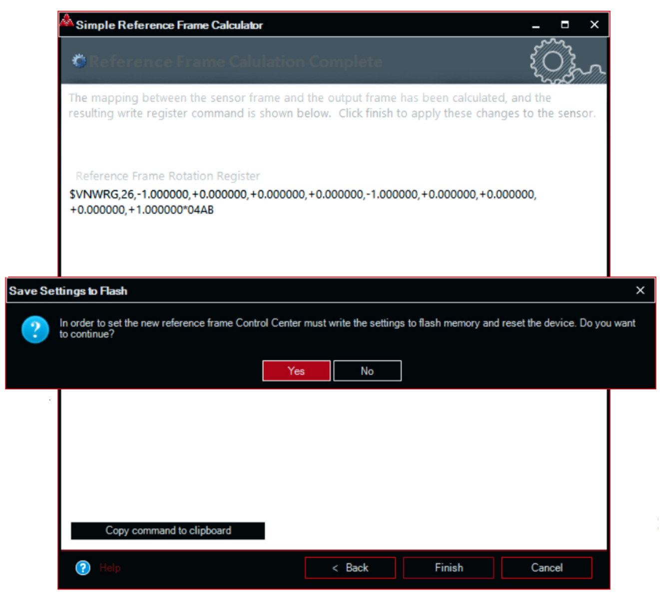
Simple Reference Frame Calculator



(a) Step 1



(b) Step 2



(c) Step 3

FIGURE 9

3. As seen in Figure 9b, select which axis of the sensor aligns with the downward axis of the body-frame (in this case the positive z-axis) and click *Next*.
4. The final step is to apply the changes to the sensor. In order to write the matrix to Register 26, click *Finish*. There will be a prompt to issue a Write Settings command and to reset the sensor. Click *Yes* as this is required to apply the changes to the sensor.

Note that the calculated sensor-to-body matrix is identical to what was calculated manually in Section 5.1.

5.3 Fine Alignment Through Advanced Reference Frame Calculator

Suppose after applying the coarse alignment rotation using one of the methods outlined in Section 5.1 or Section 5.2, it is observed that the sensor is reporting pitch and roll values of 3.9° and 5.3°, even though the body is perfectly level. Note that because gravity is used as the reference vector in this example, there is no observability of the yaw angle—it is not possible to ascertain the yaw in this case without an external sensor. A fine alignment rotation can be calculated to account for this mounting misalignment by following the explanation in Section 4.2. To do so, open the Advanced Reference Frame Calculator in Control Center and enter the negated values −3.9° and −5.3° into Rotations 2 and 3. After entering those values, press *Set Register*, and select *Yes* to the prompt to issue a Write Settings command and reset the sensor. After initializing, the sensor now reports pitch and roll angles very near [0°, 0°].

6 TROUBLESHOOTING

If any issues are encountered during the configuration of the RFR, some additional troubleshooting may be required. Below are two of the most commonly encountered issues when using an RFR. If problematic behavior persists after reviewing these troubleshooting steps, please reach out to the VectorNav support team for additional assistance.

6.1 Reference Frame Rotation Not Applied

Because the RFR gets applied at a low level and affects all measurements that are used in the filter, these settings must be saved to the non-volatile memory of the sensor through a Write Settings command after which the sensor must be reset or power cycled before the RFR takes effect.

6.2 Unexpected Sensor Behavior

If the sensor exhibits unexpected behavior after an RFR has been configured, it is recommended to:

- Ensure that the RFR has been correctly calculated and configured onto the sensor. The 3D View plot window in VectorNav's Control Center software is a great way to visualize and verify the configured RFR.
- On VN-2XX and VN-3XX products, double-check the offsets configured in Register 57, Register 157, Register 105, and Register 93 (VN-3XX only) and ensure they are specified in the body-frame.

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