HEXAGON NovAtel

APN-109

# SPAN Overview and Integration Guide

## Contents

## Introduction

SPAN stands for Synchronized Position and Attitude Navigation and refers to NovAtel's GNSS+INS combined positioning technology. Combining NovAtel GNSS with an IMU (inertial measurement unit) into an INS (inertial navigation system) filter provides:

- Continuous solutions during blocked or reduced GNSS environments.
- High-rate PVA (position/velocity/attitude) output.
- Faster satellite reacquisition.
- Smoother positioning and more…

The GNSS and IMU information is combined into an EKF (Extended Kalman Filter) using a deeply coupled integration. Using this type of architecture has many advantages over a loosely coupled implementation. A summary is shown in Table 1. These advantages allow for notable performance improvements, especially in challenging GNSS use cases.

Table 1: GNSS integration comparison

| Type of integration | Integrates GNSS Position | Integrates raw GNSS measurements | Provides Inertial information feedback to Tracking & GNSS positioning algorithms |
|---|---|---|---|
| **Loosely coupled** | ✓ | ✗ | ✗ |
| **Tightly coupled** | ✓ | ✓ | ✗ |
| **Deeply coupled** | ✓ | ✓ | ✓ |

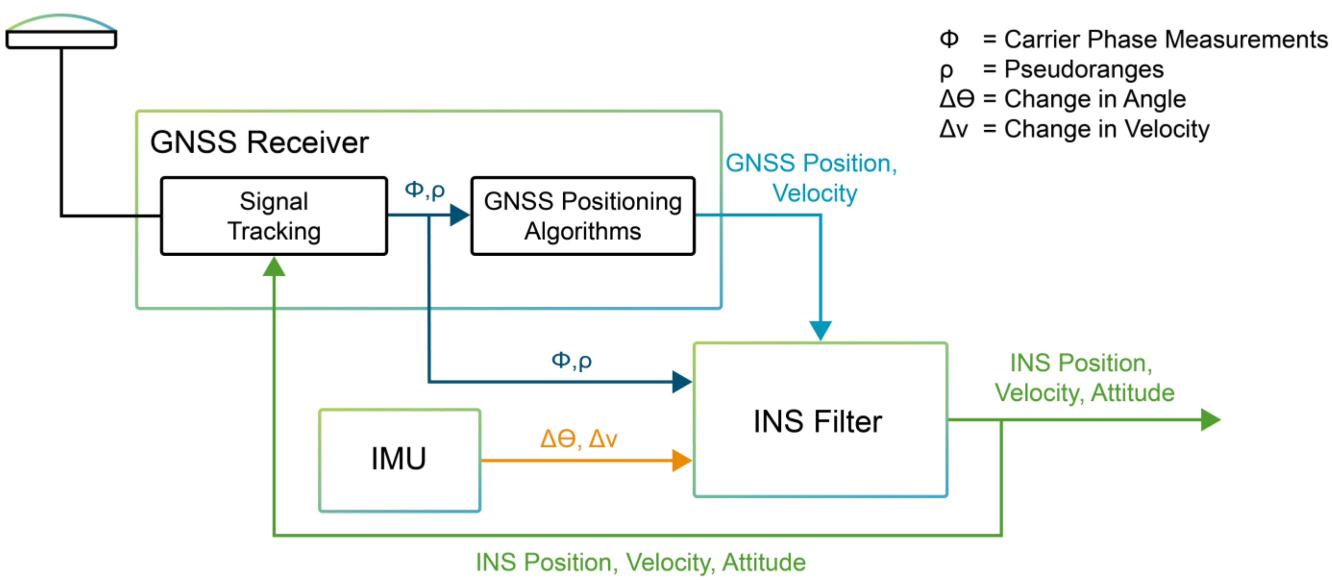

Figure 1: SPAN deeply coupled architecture

Inertial Systems will typically have very stable epoch to epoch (short duration) accuracy but will accumulate error over time. GNSS information is commonly used to aid the solution and assist in observing the accumulated inertial error, and then estimate the states responsible for the inertial error. The rate at which the inertial solution drifts depends on the sensor stability (quality), observability to estimate the sensor errors (dynamics), external environmental impacts (temperature, vibration, etc.), system configuration capability (land/rail/agriculture profile), and external sensor information provided to update the filter (DMI, LiDAR, etc.).

To achieve optimal performance with any SPAN system, there are recommended best practices in IMU and antenna mounting and specifics of the operating environment that must be taken into consideration. Neglecting any of the following will have downstream robustness, reliability, and performance impacts:

- **IMUs must be mounted rigidly** with the antenna (or antennas) and vehicle.
- Offsets between the IMU center of navigation and the phase center of the antenna(s) (known as **Lever arms**) must be fixed and accurately measured within the GNSS positioning performance mode accuracy.
- **Installation rotations** (RBV, ALIGN) should be configured as accurately as possible.
- **Initialization** and **Convergence** periods are integral to INS performance.
- Convergence period ideally contains varied motion – for a ground vehicle this includes: complete turns in varied directions, acceleration, deceleration, and periodic stops (3–5 seconds is typical).
- The **Dynamics** that are possible will depend on each customer's use case limitations, but customers should be mindful the better the convergence period dynamics are the more reliable and robust the performance will be during steady state operation.
- **Vibration** and **Temperature Variation** must be minimized as much as possible.

## How SPAN Works

When NovAtel GNSS and IMU solutions are combined, the two navigation techniques augment and enhance each other to create a powerful positioning system. The absolute position and velocity accuracy of the GNSS is used to compensate for the errors in the IMU measurements. The stable relative position of the INS can be used as a bridge to span times when the GNSS solution is degraded or unavailable. Data is available in real-time or can be post-processed for workflows requiring the most robust solution possible and additional quality control.

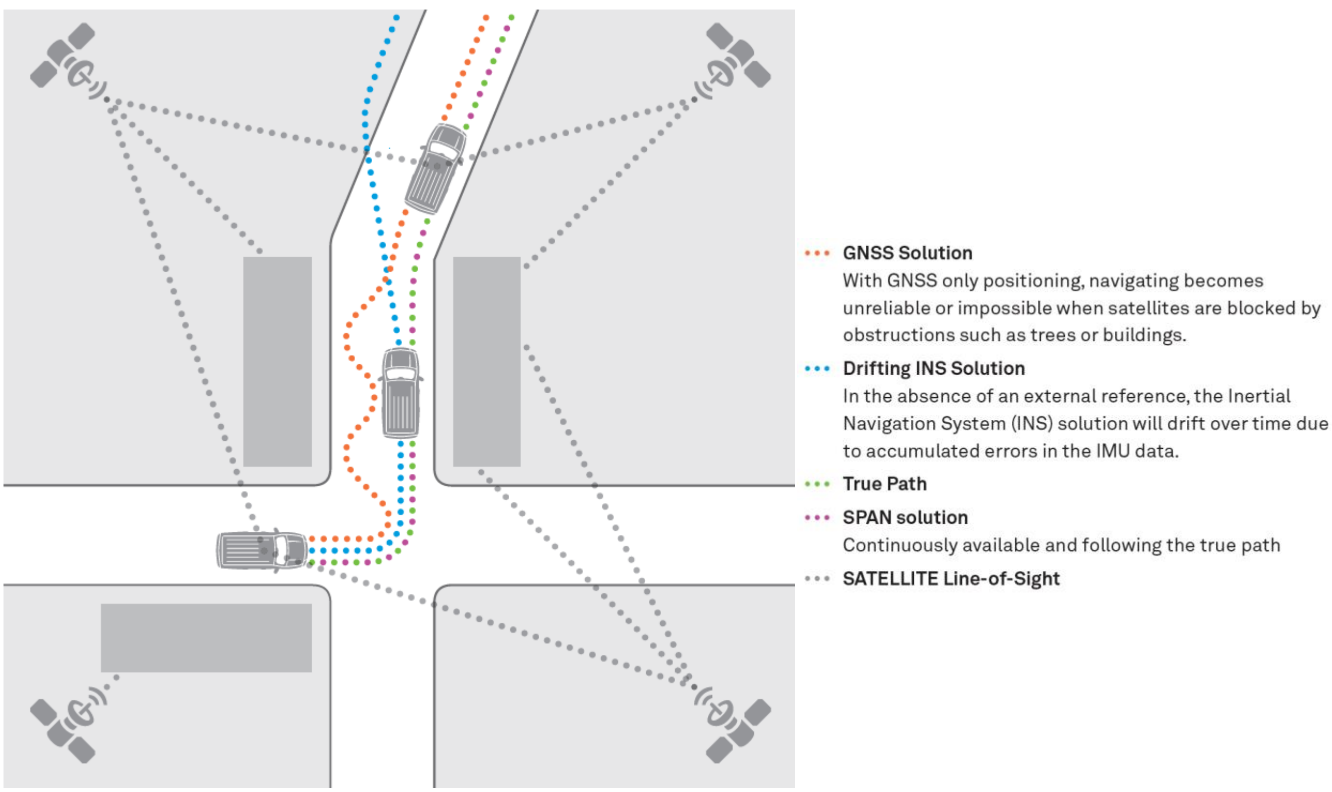


Figure 2: SPAN/GNSS/INS comparison

## Application Considerations

There are multiple factors that need to be carefully considered when selecting the right IMU or enclosure for your application:

- What GNSS conditions are you operating in: no blockage, partial blockage, full blockage, or a combination? What is the expected typical and maximum duration of those GNSS blockages?
- What are your performance requirements, are you only interested in positioning performance or high accuracy attitude?
- What type of dynamics will you be operating in? Slow moving with frequent stationary periods and use cases with lots of crab angles in your motion benefit greatly from a dual antenna solution.
- Where and how will the IMU be mounted on the vehicle? IMUs are designed to measure accelerations and small angle rotations which are easily corrupted in higher vibration environments. How each IMU reacts to vibration will be different depending on vibration levels, the physical design of each IMUs sensors as well as their internal signal processing scheme. High displacement, low frequency vibration represents actual motion of the sensor (and potentially the vehicle). High frequency vibration can cause aliasing at low frequencies and sensor errors that negatively impact performance. The vibration environment directly impacts the IMU mounting design. Generally, firm, secure mountings are required so IMU motion matches vehicle motion, but in some cases isolation mounting may be required to mitigate vibration or shock.
- What is the installed lever arm distance going to be? If you require high accuracy position and attitude, then shorter primary lever arms are always best.

## Installation

The first step in any SPAN integration is the installation of the hardware onto the platform/vehicle. The mounting method and location of the IMU and antenna is vital to the quality and robustness of the INS solution. Both the IMU and the antennas should be rigidly mounted to the vehicle and with respect to each other as this is a key assumption of a strap down inertial navigation solution like SPAN.

### Antenna Installation

Antennas need to be rigidly mounted to the vehicle with as clear a view of the sky as possible so each satellite above the horizon can be tracked without obstruction. Antenna should be mounted on a secure, stable structure capable of safe operation in the specific environment. The distance (lever arm) from the IMU to the primary antenna should be minimized as much as possible.

If using a dual antenna system, heading accuracy is dependent on antenna baseline length. Mount the primary and secondary antennas as far apart as possible (a minimum separation distance of 1 m is recommended), and for ease of operation, it is also recommended to install the antennas so that the baseline is parallel or perpendicular to the vehicle’s direction of travel.

### IMU Installation

The IMU should be rigidly mounted to the vehicle using bolts/screws where possible. It is not recommended to use duct tape, zip ties, plastic wrap, etc. IMUs can be installed in any 3D orientation with the vehicle; however, it is recommended to install with Y-axis forward, X-axis to the right, Z-axis up for ease of understanding and configuration.

The IMU should also be mounted securely in a location that is not subjected to high vibrations. For example, mounting an IMU on a cantilevered metal plate is not ideal. Choosing the best location plays a major role in reducing the vibrations exposed to the IMU. In some cases, vibration may need to be reduced or mitigated with mechanical dampers or isolators; great care will need to be taken to understand the vibration environment and selecting the appropriate hardware may be an iterative process. See Vibration for more details.

SPAN can also be configured to operate in a gimballed stabilized platform environment. In this configuration, the IMU rotates on a gimbal mount that is then rigidly mounted to the vehicle and antenna, see the Variable Lever Arm documentation for more details.

## Configuration

SPAN systems are configured either manually using commands or using NovAtel Application Suite / NovAtel Setup & Monitor (Web).

### Lever Arms

The intended function of the lever arms is to provide the necessary translation offset between two points of interest in a common reference frame. In the case of SPAN, the primary lever arm is required to co-locate the IMU center of navigation with the GNSS antenna phase center of the antenna in either the IMU body frame or vehicle frame. All NovAtel supported IMUs and antennas contain physical markers on the enclosures and detailed measurements within the documentation. SPAN provides the flexibility to enter lever arms in various frames. The IMU body frame is with respect to the IMU axis. The vehicle frame is with respect to the vehicle (X-right, Y-forward, Z-up); however, it should be noted that this frame utilizes the RBV entered by the user. Any errors or inaccuracies within the entered RBV will have a direct impact on the lever arm.

It is important to provide the lever arm as accurately as possible. Any errors included in the measurement of the lever arm will directly impact the performance and reliability of the SPAN solution. A minimum requirement is to provide a lever arm accuracy within the bounds of the GNSS positioning mode that is being used. For example, Single Point position should have a lever arm accuracy of <10 cm, RTK/PPP position modes should be <1 cm, both with standard deviations that are representative of the true error.

The standard deviation values are an important element of the lever arm and should be entered as a true representation of the lever arm uncertainty. Providing larger standard deviations will allow the SPAN filter to account for the lever arm uncertainty when applying GNSS updates. However, larger uncertainties also reduce the impact the GNSS updates have on the SPAN solution, which means the SPAN solution can show an apparent drift when compared to the GNSS.

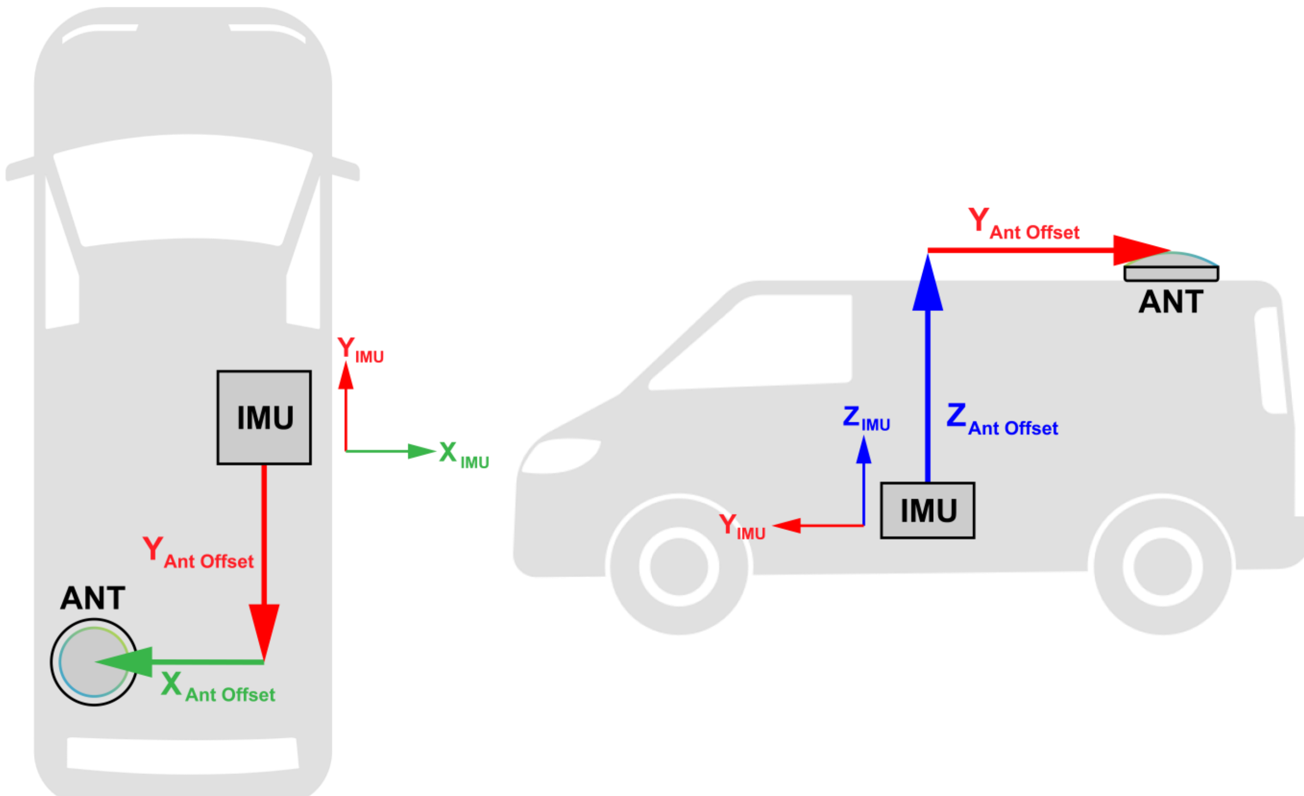


Figure 3: IMU to antenna lever arm offsets example

Using the IMU body frame, the example above shows a mounting configuration with a negative X offset, negative Y offset and positive Z offset. If the distances measured in this example were: X Offset = 1.000 m, Y Offset = 1.500 m and Z Offset = 2.000 m, the resulting lever arm SETINSTRANSLATION command using standard deviation values of 5 cm would be:

- SETINSTRANSLATION ANT1 -1.0 -1.5 2.0 0.05 0.05 0.05 IMUBODY

It is ideal to locate the IMU as close to the primary GNSS antenna as possible, this will reduce the translation distance and thus reduce the error in the aiding updates from GNSS measurements. In a dual-antenna system, it is a common misconception that the IMU should be located equidistant between both antennas. However, the secondary lever arm is only used to estimate the rotational offset between the IMU reference frame and the antenna baseline frame, it is much more beneficial to minimize the primary lever arm.

## Rotations and Offsets

The most important rotation to configure is the RBV (Rotation from the IMU Body frame to the Vehicle frame). More details on the different reference frames can be found at SPAN Reference Frames and additional details on why RBV is important as well how to calibrate it can be found at Importance of RBV Calibration.

The inertial solution is natively computed in the IMU frame, but typically, you would like to know the orientation of the vehicle. The IMU cannot sense where the vehicle frame is, it cannot sense if it is mounted upside down or backwards on the vehicle. SPAN must be supplied this information to transform the solution from the IMU reference frame to something meaningful, which is often the vehicle frame. The vehicle frame to IMU body also must be known for GNSS course over ground information to be used to aid the inertial solution.

If the RBV rotation has been configured, the default output of the SPAN solution will be in vehicle frame; however, if a USER rotation has also been entered, that will take precedence for the output frame.

All use cases should configure the rotation between the IMU Body Frame and Vehicle Frame. The RBV is utilized by various internal updates and applied if translation offsets are entered in the vehicle frame (as mentioned above). It is also mandatory for achieving kinematic alignments, a common alignment method for many applications. All rotations are handled by SPAN as intrinsic rotations in **Z**>**X**>**Y** order, this means the axes change their orientation after each elemental rotation.

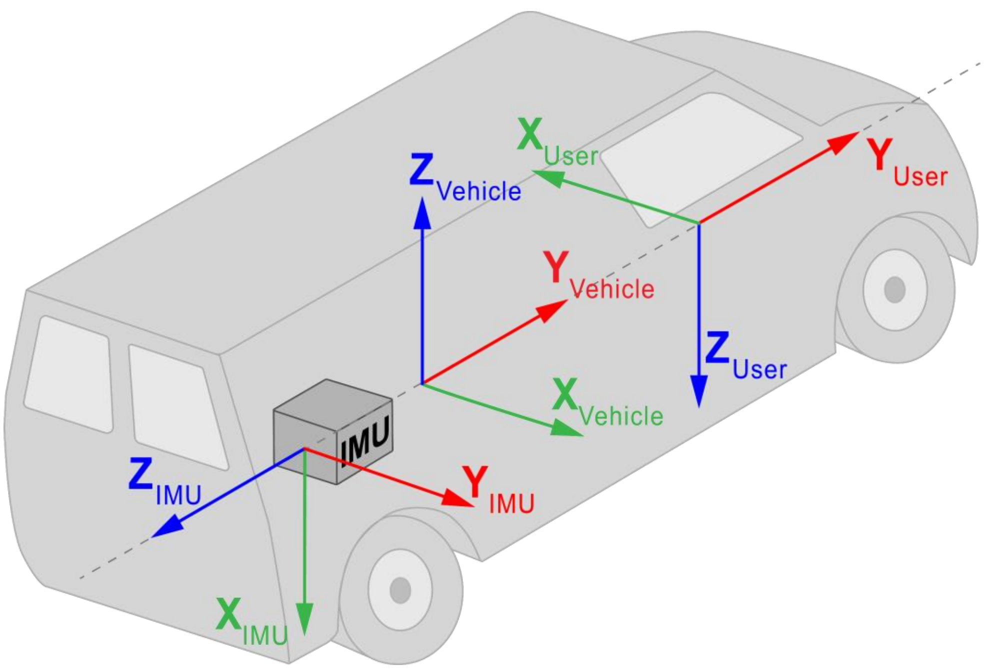

Figure 4: IMU, vehicle and user rotation example

Above is an example of a potential installation orientation, where the Y-vehicle is the forward motion direction, and Z-vehicle is up. The resulting RBV and USER rotation SETINSROTATION commands would be:

- SETINSROTATION RBV -90 0 90 3 3 3
- SETINSROTATION USER -90 0 -90

Standard deviation values for RBV rotations can also be supplied and should be representative of the measurement accuracy. The values entered should not be overly optimistic (i.e., err on the side of a larger standard deviation), we recommend standard deviations of 3 degrees for a typical setup.

There are several additional rotations and translation offsets that can be configured, ranging from mandatory to optional given customer requirements. For example, you may want to see the PVA solution in a camera frame instead the vehicle frame. Please refer to the documentation (Rotation/Translation) for more information.

## Initialization

Initialization is the first and most important step of all SPAN systems real time operation; the effectiveness of this stage can have lasting impacts on the performance throughout operation. Initialization means telling the IMU where it is on the surface of the earth and how it is oriented, so that the IMU errors can be observed and accurately estimated. Initialization can be broken down into two phases, the alignment and the convergence phase.

### *Alignment Phase*

The main objective of the alignment phase is to obtain an initial azimuth to set the IMU orientation. Various options for providing this estimate are listed below.

- **Static Coarse Alignment** – Gyro compassing is used to determine north using only IMU measurements while stationary. Requires IMUs that can gyro compass (typically IMU Grade 2+), stationary environment, and an initial position.
- **Kinematic GNSS course over ground** – North is defined by the GNSS course over ground and the IMU orientation is initialized based on the GNSS course over ground and the known RBV rotation. Must have a correct RBV rotation configured and forward motion in a straight line. Crab angles (typically observed in marine or aerial environments) will induce a bias to the kinematic alignment and should be minimized during the Kinematic Alignment routine. Calibration of the RBV is an option if it's not accurately known.
- **Dual antenna ('Aided Transfer')** – In this case, the IMU orientation is initialized based on the computed ALIGN heading values and the known rotation between the ALIGN baseline and the IMU frame. Crab angles are no longer an issue. Requires correct ALIGN rotation configuration.
- **Manual command** – SETINITAZIMUTH or EXTERNALPVAS commands. The user or external system is responsible for correctly supplying an initial estimate for the azimuth and appropriate confidence values.
- **INS Seed** – Saved and re-validated azimuths from prior operation (requires vehicle to have remained stationary). The IMU orientation is initialized with the orientation saved at last power off.

For lower end performance sensors, it is also recommended to include a short static period at beginning of operation to complete a static IMU bias estimation. This process involves a short ~10 second stationary period after receiving IMU data and prior to providing the initial azimuth. If the IMU is not moving, the gross IMU errors can more easily be separated from observed vehicle motion effects. The only remaining motion is Earth's rotation, which is far below the noise and bias level of most MEMS-based IMUs. This data can be used to compute rough estimates for the IMU sensor biases to inject into SPAN's initialization and reduce overall time to a robust convergence. Static periods (at the beginning and end of a collection) are also preferred for post-processing applications. Alternatively, the INS Seed functionality can be used to inject saved error states from a previous run as an initial estimation.

### *Convergence Phase*

The convergence phase is the next step of initialization, starting after initial azimuth is injected/computed and when motion begins. During this phase, the INS filter is using the observed motion and GNSS information to fine tune the IMU error state estimates. The performance and robustness of the INS Solution throughout the rest of operation is dependent on the quality of the convergence period.

For optimal convergence, it is recommended to incorporate as much vehicle motion as possible. For a ground vehicle, this includes complete turns in opposite directions, acceleration, deceleration, and periodic stops (3–5 seconds is typical). Horizontal accelerations allow azimuth error to be observed and corrected.

The INS filter confidence can be monitored through the inertial standard deviations, which are an estimate of the SPAN filter's confidence in its solution, it should not be assumed they are an accurate representation of the true error.

## Other Considerations

### Vibration

Vibration is an extremely important and challenging factor to characterize. It can be the difference between obtaining expected INS performance and observing catastrophic failures. Vibration is a system design problem because it depends on the IMU hardware and signal processing design as well as the operating environment, which includes the vehicle dynamics, mounting location, etc. For example, the vibration experienced by an IMU mounted on a tractor depends on the type of ground cover the tractor is driving over (and whether it is compacted or frozen), tire inflation level (or is it tracks rather than tires), speed of travel over the ground, gear and throttle selection, engine type, and mounting location of the IMU. That physical environment decides what vibrations the IMU is exposed to. The quality of the measurements (with regards to usefulness in measuring the trajectory travelled) produced by the IMU under that vibration will depend on the IMU's hardware and signal processing design.

It is the responsibility of the system designer and integrators to be mindful of this during the entirety of development, just as they consider power consumption, cost, weight, or reliability. Due to the difficulty and importance in managing vibration, it should be considered early in the system design so that proper mounting locations can be chosen. Reinforced hardware (isolation or damping mounts) should be used if necessary and iteratively tested and updated to ensure the vibration is being mitigated appropriately. Some levels of vibration will be acceptable and have no negative impacts, but in general any reductions in vibration will improve the performance. Every IMU has unique methods of sampling the data, physical properties of the sensors, mounting and filtering of the raw data, which can lead to different IMUs performing better or worse under the same conditions. The vibration 'signal' that ends up in the passband of the IMU measurements is indistinguishable from true motion.

The SPAN filter will integrate that 'signal' without knowledge or warning causing a degradation in performance; the rate of degradation will vary and depend on dynamics, the GNSS environment, external sensor updates that are available, the specific IMU, and the characteristics of the vibration. Once measurements are digitized, there is no way to correct the corrupted information from the IMU data that bleeds into the raw measurement's domain.

Vibration issues are most successfully solved in hardware re-design, either by changing the mounting location of the IMU and/or damping the vibration of the IMU location. This is often a very difficult activity to take on later into a design phase and is highly recommend being cognizant of the potential impacts and monitor early in the design phase.

In general, any reduction in vibration will be beneficial for the reliability and robustness of the INS solution. Ensure that all other integrated sensors (e.g., cameras or LiDAR) are installed with the IMU. These all need to be very rigidly mounted together so any damping of vibration would need to be done to the mount where both are rigidly fixed.

## Dynamic Range

Dynamic range refers to the measurement limits that the sensor will provide accurate data for. Going beyond those limits will result in poor or invalid data being integrated by the filter, introducing error and degrading performance. To avoid this complication, it is imperative that the acceleration and rotation limits of the application are understood, and the correct sensor is selected.

Every IMU part comes pre-configured with a specific dynamic range for the accelerometers and gyroscopes, multiple dynamic range options for each IMU are not supported. Information on IMU dynamic range specifications can be found here.

## Temperature and Sensor Variation

Every IMU sensor is manufactured to meet datasheet performance specifications. However, it is helpful to understand that there can be varied sensor behaviors within those specifications that can impact the performance of an INS filter. Typically, this is managed internally with good observability of the sensor information (dynamics) and good GNSS conditions, allowing proper modelling of the sensor error states.

Sensor characteristics can vary with temperature, and rapid or wide temperature swings, can increase sensor errors, and degrade the overall INS performance. This is especially acute during a GNSS blockage where sensor error observability is limited.

## Dynamics

The characteristics of vehicle motion is referred to as dynamics. Low dynamics means infrequent or no turns, and low or no acceleration. High dynamics means lots of changes in velocity (heading and speed). For clarification, agricultural, heavy construction vehicles and large vessels typically have low dynamics, whilst on-road vehicles and aircraft typically have high dynamics. In use cases where the vehicle is only capable of low dynamics (limited turns, accelerations, or speeds), additional supporting sensors should be considered depending on performance requirements, IMU choice and performance expectations. In these low dynamic environments, it becomes increasingly difficult to accurately model the error states of the IMU or filter; supporting sensors can provide important updates to maintain accuracy and reliability. Dual antenna ALIGN, DMI, or external updates are some options that might be helpful for any given use case.

In applications that involve land, agriculture, or rail vehicles, configuring the INS Profile can be done to help reduce error growth by using intelligent vehicle dynamics modeling. This is of significant benefit in long, complete GNSS outages.

## External Updates

External Updates are a more advanced user feature within the SPAN software. When used properly, External Updates maintain high quality INS Solutions while in challenging or denied GNSS environments. “Used properly” means the external update is an accurate and helpful update to the system, the quality indicator associated with the update correctly represents the accuracy, and it is provided quickly enough (low latency) to the SPAN system that the information isn't degraded in value. Due to the technical difficulties in implementing it correctly, this feature may not be a solution for every user.

Information on this feature can be found within the External PVA Feature Application Note, and the EXTERNALPVAS command documentation details all the current forms of external updates that can be accepted, ranging from absolute position/velocity/attitude updates to relative epoch-epoch position/attitude updates. If you would like more information about this feature, please contact NovAtel Support.

# Acronyms and Links

## Acronym List

| | |
|---|---|
| **DMI** | Distance Measurement Instrument |
| **EKF** | Extended Kalman Filter |
| **GNSS** | Global Navigation Satellite System |
| **IMU** | Inertial Measurement Unit |
| **PPP** | Precise Point Positioning |
| **RTK** | Real-Time Kinematic |
| **SPAN** | Synchronized Position & Attitude Navigation |

## Additional Resources

### *NovAtel Website*

- SPAN Supported IMUs
- SPAN Brochure
- SPAN Reference Frames
- SPAN LAND Profile
- FW Options
- NovAtel Application Notes

### *Documentation Portal*

- SPAN Installation
- SPAN Operation
- SPAN Commands
- SPAN Logs
- SPAN INS Profiles

## Support

To help answer questions and/or diagnose any technical issues that may occur, the NovAtel Support website is a first resource.

Remaining questions or issues, including requests for test subscriptions or activation resends, can be directed to NovAtel Support.

Before contacting Support, it is helpful to collect data from the receiver to help investigate and diagnose any performance-related issues. A list of appropriate troubleshooting logs can be found on the OEM7 Documentation Portal (the LOG command with the recommended trigger and data rate is included with each log).

The data described above can be collected using the NovAtel Application Suite.

## Documentation

For any questions on logs and command, please visit the OEM7 Documentation Portal.

Contact Hexagon | NovAtel

support.novatel@hexagon.com 1-800-NOVATEL (U.S. and Canada) or 1-403-295-4900
For more contact information, please visit novatel.com/contact-us