

PHOENIX
LiDAR SYSTEMS

IMU Heading Drift Rate Analysis



A PHOENIX LiDAR CASE STUDY

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INTRODUCTION

LiDAR remote sensing systems utilizing GNSS/INS are reliant on the integration of an accurate Inertial Measurement Unit (IMU) to achieve high quality data. The IMU forms the core of the navigation system, which is used to estimate a trajectory. This trajectory is then used for georeferencing (“fusing”) raw LiDAR range data into a point cloud. IMUs vary in terms of performance and price, so selecting the right IMU for a given LiDAR application is an important step.

IMU hardware collects data from gyroscopes and accelerometers. Gyroscopes, which are used to measure rates of rotation along 3 axes (roll, pitch, and yaw), have inherent measurement imperfections. When a gyroscope is stationary and not rotating, output measurements, which should be constant due to the lack of rotation, will in fact change, or drift, over time. It’s important to consider that an IMU may drift along certain axes, even when not completely stationary. For example, traveling with a constant heading means that the gyroscope associated with measuring heading is nearly at rest, and subject to drift. Drift along the heading axis is typically more impactful than the drift observed along the pitch and roll axes, as “A good portion of the pitch (attitude) and roll axis gyroscope drift can be removed within an IMU through the use of accelerometer feedback to monitor position relative to gravity” (Analog Devices, 2017).

Heading drift is most pronounced when a vehicle travels in a relatively straight path for a prolonged period of time, as heading estimates degrade in accuracy due to an accumulation of gyroscope noise. This is particularly problematic with aerial LiDAR data acquisition, as single-grid type and corridor acquisitions must take into account how long the IMU can travel in a straight path without accumulating too much drift. To mitigate this, operators will typically limit their flight line lengths accordingly, or perform dynamic maneuvers in the middle of long flight lines.

What is too much drift, and how does it vary between different IMU grades? In this paper, four IMUs were evaluated based on their ability to maintain an accurate heading during a long-duration flight line. Real-world data was used to determine IMU heading drift rates, which express how much the IMU heading error increases over time. We also discuss the resulting effect of angular attitude errors on LiDAR range measurements at different altitudes, to give the reader an idea of what type of positional errors will result from a given heading error.

METHODOLOGY

Four IMUs were evaluated based on their ability to maintain an accurate heading when traveling with a constant heading. The IMUs analyzed are summarized in the table below:

| | IMU TYPE | WEIGHT (grams) | GYRO BIAS INSTABILITY* |
|----------|----------|----------------|------------------------|
| IMU - 27 | MEMS | 55 | 0.3°/hr |
| IMU - 30 | MEMS | 200 | 0.45°/hr |
| IMU - 33 | FOG | 700 | 0.05°/hr |
| IMU - 60 | FOG | 2500 | 0.05°/hr |

Table 1: IMU Information and gyro bias instabilities.

IMUs are described as being either a Micro-Electro-Mechanical System (MEMS) or Fiber-Optic Gyro (FOG) IMU. MEMS IMUs are typically smaller and lighter than FOG IMUs, however FOG IMUs typically have more stable gyroscopes. This is evident in the Gyro Bias Instability column. Gyro bias instability refers to the amount that an IMU's gyroscope bias will drift over time during operation, and is sometimes referred to as in-run bias error. This value represents the attitude error that one would expect in real-time during an unaided period (i.e. a GNSS outage, or in this case of heading error, a long flight line).

LiDAR positioning applications involve the use of post-mission processing (e.g. NavLab or InertialExplorer), which includes the Rauch-Tung-Striebel (RTS) backsmoother, as well as the ability to combine forward and reverse directions. The RTS smoother can reduce the effect of the drift significantly, as it has a good estimation of the expected IMU error behavior via its advanced error modeling, which takes into account the IMU performance as well as GNSS accuracy and flight dynamics. So, while gyro bias instability is an important specification that helps us determine the quality and accuracy of an IMU, we shouldn't expect our results to exactly equal the manufacturers' gyro bias instability specifications, as we are using post-processed data.

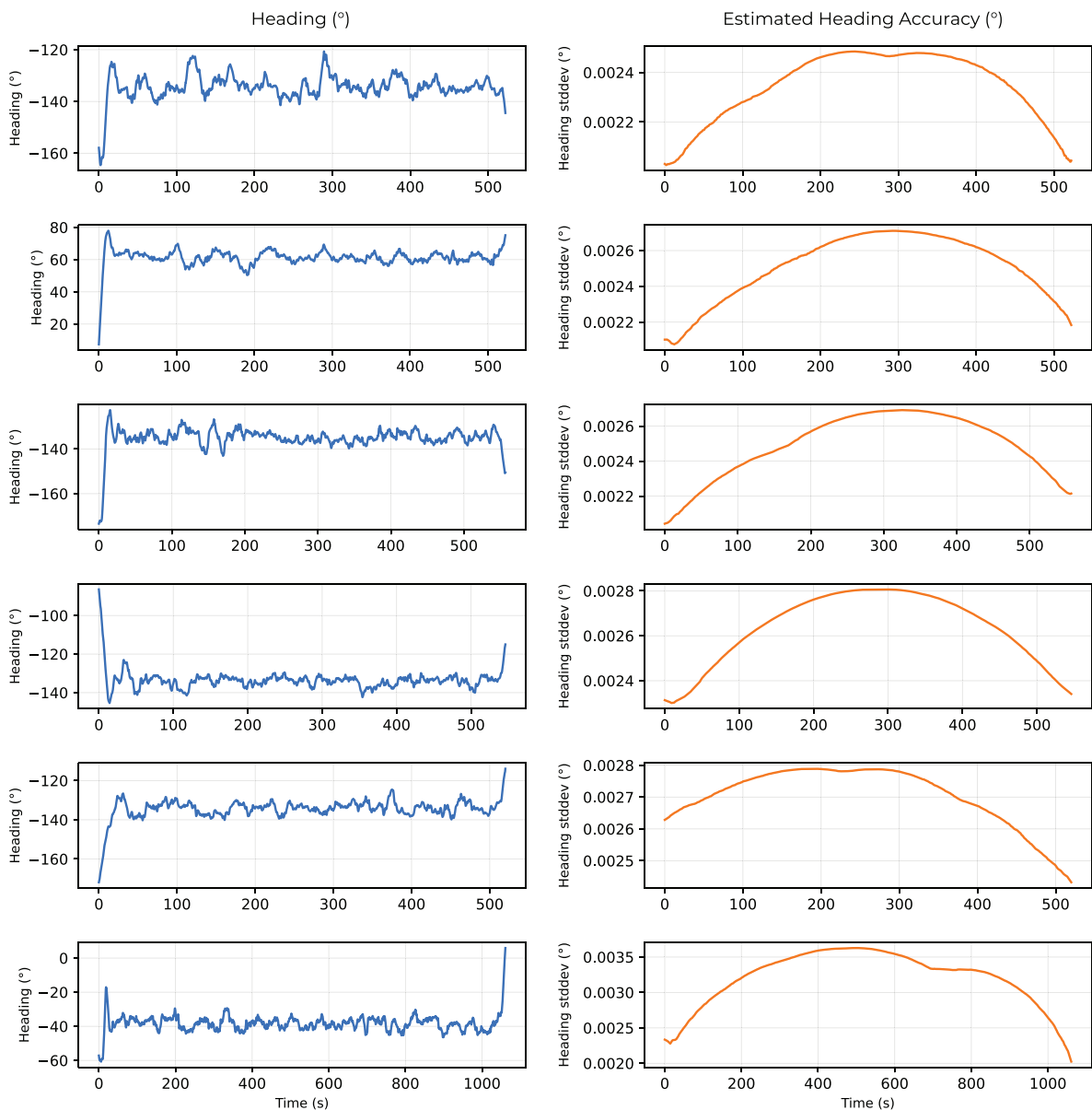
For each IMU, heading drift was analyzed using aerial data sets, particularly data sets acquired via helicopter or fixed wing aircraft. Missions with long and straight flight lines were most suitable for this evaluation. NovAtel's InertialExplorer software was used to post-process trajectories and export estimated heading accuracy information.

*Gyro bias instability values reported from manufacturer data sheets. ("Inertial Measurement Units", Hexagon, 2025)

METHODOLOGY

Heading drift can be observed as an increase in the estimated heading error when the vehicle maintains a relatively constant heading for a prolonged period of time. Flight lines were extracted from each data set based on the following criteria:

1. Heading variation of less than 15 degrees*
2. Duration was at least 100 seconds
3. Vehicle speed was at least 10 m/s



*Heading variation was determined by computing the standard deviation of heading values during the flight line.

METHODOLOGY

For each flight line, the increase in IMU heading error was computed by subtracting the minimum heading error during the flight line from maximum heading error during the flight line.* The minimum heading error typically corresponded with the beginning or end of the flight line, while the maximum heading error typically occurred near the middle of the flight line.

Readers may expect that the maximum heading error would occur near the end of the flight line, as IMU drift accumulates over time during long flight lines, however dual-pass processing (forward and reverse) performed by Inertial Explorer results in the middle of the flight line exhibiting the most error. In other words, the middle of the flight line is furthest in time from any change in heading or turns, which would help reduce drift. Trajectory back smoothing also impacts the estimated heading error - this is discussed further in the 'Discussion' section.

For each IMU, the increase in heading error versus the duration of the flight line was plotted on a scatter plot. A linear regression was performed to determine a heading drift rate for the IMU, in degrees per hour, that best models the data.

*Heading error is expressed in terms of heading standard deviation in degrees, so to compute the difference in standard deviation, variances were subtracted and a new standard deviation was computed from that.

RESULTS

IMU drift rate results were computed from the data. Drift rates are expressed in degrees per hour, which is the same unit commonly used to express gyro bias instability specifications. The IMU-27 exhibited the highest rate of drift, at 0.1480°/hr. The IMU-30 and IMU-33 showed similar drift rates, of 0.0833°/hr and 0.0878°/hr respectively. The IMU-60 exhibited the lowest drift rate of 0.0135°/hr.

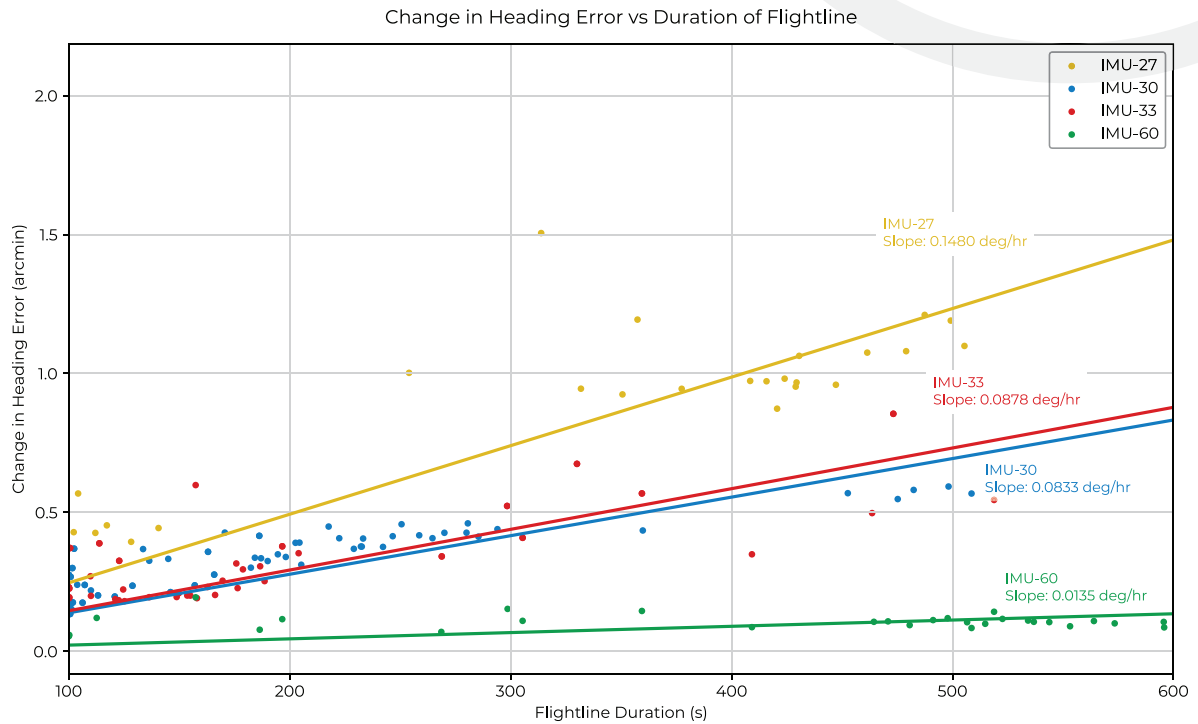


Figure 2: Change in heading error versus the duration of flight line is shown for each IMU on a scatter plot. Best-fit regression lines through the data show the drift rate of each IMU.

All IMUs exhibited drift rates lower than their respective gyro bias instability specifications, except for the IMU-33. As mentioned in the introduction, post-processing techniques, such as forward-reverse combined solutions and RTS backsmoothing, enable producing results that exceed the manufacturers' gyro bias instability specifications. Notably, the IMU-30, a MEMS IMU, performed similarly in our test to the IMU-33, a heavier, FOG IMU.

DISCUSSION

HEADING DRIFT EFFECT ON LiDAR ACCURACY

IMU drift rates, expressed in degrees per hour, help us compare the IMU heading estimate stability between IMUs, but don't tell us directly about the resulting point cloud accuracy. LiDAR pulse positioning error due to navigation system heading error is a function of the LiDAR pulse range. To get an idea about how much heading drift is too much, we can determine the LiDAR pulse positioning error that would result at different altitudes for each IMU drift rate.

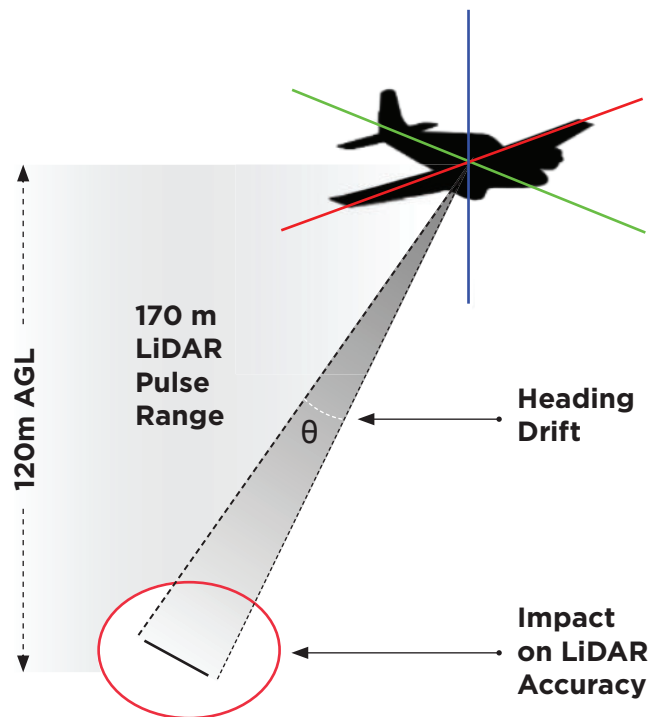


FIGURE 3: How heading angle errors impact LiDAR accuracy

IMU heading drift over 5 minutes was computed using the drift rates shown in figure 2. The drift calculated for each IMU over 5 minutes is then used to derive the influence on the point cloud accuracy from a 25° scan angle from various above ground levels (AGLs). By using a 25° scan angle scenario, we show what would likely be a typical point cloud georeferencing error due to this angular heading error for a typical aerial data set.

DISCUSSION

| | HEADING DRIFT | IMPACT AFTER 5 MINUTES ON LIDAR @ 25° SCAN ANGLE | | | |
|----------|---------------|--|----------|----------|----------|
| | DRIFT RATE | 150M AGL | 300M AGL | 500M AGL | 700M AGL |
| IMU - 27 | 0.1480°/hr | 0.036 m | 0.071 m | 0.119 m | 0.166 m |
| IMU - 30 | 0.0833°/hr | 0.020 m | 0.040 m | 0.067 m | 0.094 m |
| IMU - 33 | 0.0878°/hr | 0.021 m | 0.042 m | 0.070 m | 0.099 m |
| IMU - 60 | 0.0135°/hr | 0.003 m | 0.006 m | 0.011 m | 0.015 m |

Table 2: Evaluated attitude accuracy residuals and extrapolated LiDAR impact.

AGL AND MISSION TYPES

Table 2 shows that after 5 minutes of drift, IMU heading error introduces substantial error into a point cloud. We also see that the planned LiDAR data acquisition altitude, or AGL flying height, has considerable implications when determining the right IMU for a LiDAR system. At higher AGLs, the IMU drift rate introduces larger errors in the point cloud. At 150m AGL, 5 minutes of drift produces about 2 cm of point cloud positioning error with the IMU-30, which may be acceptable depending on project accuracy requirements.

For many LiDAR acquisitions it may be unnecessary to prepare for 5 minute flight lines. The expected length of flight lines in a LiDAR mapping mission is important to consider. For wide-area mapping flights, flight lines are typically shorter, so it may be reasonable to assume that flight lines will be only 2 to 3 minutes in duration. Corridor-style mapping missions typically involve mapping long, linear infrastructure features. In these scenarios, it may be completely reasonable and desirable to fly in a straight path for over 10 minutes.

CONCLUSION

IMUs have intrinsic heading drift rates which ultimately affect the accuracy of the navigation system and resultant LiDAR point cloud data. The LiDAR pulse positioning error caused by angular heading error varies with the LiDAR pulse range, which is a function of acquisition AGL and scan angle. For instance, from table 2 we see that a 0.007° heading error results in a 2 cm point cloud georeferencing error at 150 m AGL. However, at 500 m AGL, the georeferencing error is 7 cm. This means that the amount of heading error the user can tolerate is a function of acquisition AGL.

Ultimately, some navigation system heading error is unavoidable, and LiDAR systems should use IMUs that make sense for the application. MEMS IMUs, such as the IMU-27, can maintain a sufficiently stable heading for acquiring corridor-style data sets at UAV altitudes, around 120 m AGL. LiDAR systems designed for high-altitude mapping acquisitions, where grid-pattern flight lines regularly exceed 5 minutes, should make use of highly accurate FOG IMUs, such as the IMU-60, which can maintain an extremely stable heading over long durations.

REFERENCES

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