Tolerance Analysis of the “Treexalerator” IMU–Encoder Test Rig Using an AksIM-2 MB064 Absolute Encoder

Taylan Arslan

November 26, 2025

Abstract

This report derives mechanical tolerances for the “Treexalerator” test rig, a rotating platform designed to characterise inertial measurement units (IMUs) by comparison with an absolute magnetic encoder. The rig uses an RLS AksIM-2 MB064 readhead paired with an MRA064BC040DSE00 magnetic ring and is driven by a CubeMars GL60 gimbal motor. Starting from the encoder manufacturer’s installation tolerances (ride height, radial and tangential misalignment, and allowed tilt), we translate these into requirements on the 3D-printed and machined components of the structure: plate parallelism, shaft and ring concentricity, readhead placement and mounting stack-up. The objective is to ensure that the mechanical errors of the rig are significantly smaller than the IMU errors under test, so that the comparison is limited by sensor characteristics rather than fixture imperfections.

1 Introduction

In order to evaluate IMU accuracy and stability under controlled rotation, it is useful to compare the IMU output with a reference angle source that has significantly better accuracy than the IMU. Absolute encoders based on magnetised rings and contactless readheads are well suited to this role, provided that their installation tolerances are carefully respected.

The Treexalerator test rig is a compact rotating structure that mounts an IMU on a perforated platform between two side plates. One end of a hollow shaft is driven by a CubeMars GL60 gimbal motor; the other end carries an RLS MRA064BC040DSE00 magnetic ring. An MB064 readhead is fixed to the structure so that it senses the ring while the entire assembly rotates. By logging encoder angle and IMU output simultaneously, the IMU’s bias, noise and scale factor errors can be characterised.

Because the encoder’s specified installation tolerances are relatively loose compared to its intrinsic resolution, there is a risk of building a mechanically poor fixture that still satisfies the minimum datasheet limits but introduces larger angular errors than the IMU being tested. The goal of this report is therefore to use the encoder datasheet quantitatively to derive *design* tolerances that are stricter than the bare minimum, but still achievable with a combination of 3D printing and light machining. Gemini 3.0 was used to edit this report for coherence and grammar.

2 Encoder and Motor Overview

2.1 AksIM-2 MB064 encoder and MRA064 magnetic ring

The RLS AksIM-2 MB series is a family of off-axis absolute magnetic encoders consisting of a magnetised ring and a static readhead PCB. For the MB064 readhead with an MRA064 ring, the relevant installation tolerances are summarised in the datasheet as follows:

- The axial distance between sensor and ring (the ride height) must lie between 0.05 mm and 0.35 mm. This distance is controlled indirectly via a "mounting dimension" shown in detail A of the assembly drawings.
- Tangential displacement of the readhead relative to the ring is allowed up to ±0.3 mm.
- Radial displacement of the readhead is allowed up to ±0.5 mm for MB064.
- Non-parallel mounting of the ring and readhead is limited by a maximum tilt angle of 0.2°.

The installation section also recommends using the gold-plated bottom surface of the readhead as the mechanical reference plane, notes that increasing ride height within the allowed range increases output noise, and provides a logarithmic relation between an internal signal-level metric and the ride height,

$$h = K \ln(\text{SignalLevel}) + N, \tag{1}$$

where h is the ride height and K, N are size-dependent constants. The calculated ride height is specified to have a tolerance of ±20 µm.

Within the family of MRA064 rings, the mechanical drawing for a ring with extended inner diameter (MRA064BG051DSN00) specifies an outer diameter of

$$D_{\text{out}} = 64\,\text{mm} \pm 0.1\,\text{mm}, \tag{2}$$

$$t = 2.0\,\text{mm} \pm 0.05\,\text{mm}, \tag{3}$$

with the inner diameter carrying an H7 tolerance and mounting holes for M2.5 fasteners. Although the exact drawing for the MRA064BC040DSE00 (with 40 mm inner diameter) is not reproduced here, it is reasonable to assume the same outer diameter, thickness and tolerance class for the present analysis, as these are consistent across the family.

For smaller ring sizes (e.g. MRA022 and MRA029) the datasheet recommends shaft diameter tolerances such as D8 r6 or D12.7 p7 for press-fit mounting, which correspond to typical interference fits with radial clearances well below 0.02 mm. This gives useful guidance on the level of concentricity the manufacturer considers appropriate when the ring is directly referenced to a shaft.

2.2 CubeMars GL60 gimbal motor

The rotary motion is provided by a CubeMars GL60 KV25 gimbal motor. According to the manufacturer's technical drawing, the key mechanical features relevant to this analysis are:

- Outer diameter: 69 mm.
- Axial length: 22.3 mm.
- Hollow shaft diameter: 20 mm.
- Mounting patterns: 4 × M3 on a 40 mm pitch-circle diameter (PCD) and 4 × M2.5 on a 50 mm PCD.

The large hollow shaft allows routing of encoder and IMU cabling and simplifies concentric mounting of the MRA064 ring on an adapter attached to the motor shaft or hub.

3 Mechanical Design of the Treexalerator

3.1 Geometry

The Treexalerator consists of two end plates connected by a rectangular deck. The deck carries a grid of threaded holes for mounting IMUs and other instrumentation. The end plates have approximately elliptical outlines with a maximum radius of about 62.5 mm and are separated by a distance of order 100 mm. The main shaft passes through both plates with a nominal diameter of 17 mm. Axial length of the complete assembly is approximately 147 mm.

One end of the shaft is coupled to the GL60 motor; the other end carries the MRA064 magnetic ring. The MB064 readhead is fixed to the encoder-side plate such that its sensing area is centred over the ring and at the correct ride height. The IMU is bolted to the deck at a known radius relative to the shaft axis.

3.2 Coordinate system and error sources

Throughout this report we define:

- The z-axis as the nominal shaft axis, oriented from motor towards encoder.
- The x–y plane as the nominal plane of the magnetic ring.
- Angular position θ as the rotation of the ring about the z-axis measured by the encoder.

Mechanical imperfections in the test rig can be grouped into:

1. **Axial errors** affecting ride height: stack-up tolerances, plate separation, ring axial runout.
2. **Radial errors** affecting eccentricity: misalignment between shaft, ring, and readhead.
3. **Tilt and non-parallelism**: deviation of the ring plane from the readhead plane.
4. **Deck alignment errors**: deviation between the shaft axis and the IMU rotation axis.

We now relate each category to the encoder installation limits and derive practical tolerance targets.

4 Deriving Tolerance Requirements from the Datasheet

4.1 Notation

Let

- R = effective magnetic radius of the ring (half of the outer diameter).
- h = local ride height (sensor–ring distance).
- Δh = peak-to-peak variation in ride height over the ring radius.
- e = radial eccentricity between ring centre and readhead arc centre.
- α = tilt angle between ring plane and readhead plane.

For an MRA064 ring with $D_{\text{out}} \approx 64$ mm we take

$$R = \frac{D_{\text{out}}}{2} \approx 32\,\text{mm}. \tag{4}$$

4.2 Tilt and plate parallelism

The datasheet limits the tilt between ring and readhead planes to $\alpha < 0.2°$. For a small tilt angle, the height difference between opposite edges of the ring is

$$\Delta h \approx R \tan \alpha. \tag{5}$$

Substituting $R = 32\,\mathrm{mm}$ and $\alpha = 0.2°$,

$$\Delta h_{\mathrm{max}} \approx 32\,\mathrm{mm}\tan(0.2°) \approx 0.112\,\mathrm{mm}. \tag{6}$$

This means that, even if the mean ride height is perfectly centred in the allowed 0.05 mm–0.35 mm window, non-parallelism approaching the datasheet limit will cause variations of roughly 0.1 mm in local gap. To maintain margin and reduce sensitivity to assembly errors, it is reasonable to impose a stricter design requirement on the Treexalerator plates:

$$\Delta h_{\mathrm{design}} \leq 0.05\,\mathrm{mm} \quad \Rightarrow \quad \alpha_{\mathrm{design}} \lesssim \arctan\left(\frac{0.05}{32}\right) \approx 0.09°. \tag{7}$$

In GD&T (Geometric dimensioning and tolerancing) terms this can be expressed as a parallelism tolerance of 0.05 mm between the encoder-side plate face that carries the readhead and the mechanical reference plane defined by the motor-side plate or shaft axis.

4.3 Ride height and stack-up of axial dimensions

The encoder manufacturer specifies that the ride height must be kept within 0.05 mm to 0.35 mm. In addition, the documentation states that a "tight ride height is recommended" because increasing the distance increases encoder noise even when within the allowed range. A sensible design goal is therefore to aim at the centre of the allowed interval, $h_0 \approx 0.2\,\mathrm{mm}$, with a total worst-case tolerance smaller than $\pm 0.1\,\mathrm{mm}$.

Let the mounting dimension from the readhead reference surface to a machined shoulder on the shaft be M. The ride height is then

$$h = M - t_{\mathrm{ring}} - t_{\mathrm{adhesive}} - t_{\mathrm{shim}}, \tag{8}$$

where t_{ring} is the ring thickness, t_{adhesive} represents any adhesive layer between shaft and ring, and t_{shim} accounts for intentional shimming under the readhead. Taking $t_{\mathrm{ring}} = 2.0\,\mathrm{mm} \pm 0.05\,\mathrm{mm}$ from the family drawing and assuming a thin adhesive layer ($\sim 0.02\,\mathrm{mm}$), the main controllable quantities are M and t_{shim}.

The total axial tolerance on h can be written as

$$\delta h \approx \sqrt{\delta M^2 + \delta t_{\mathrm{ring}}^2 + \delta t_{\mathrm{shim}}^2}, \tag{9}$$

where δx denotes the manufacturing tolerance on x. If we choose

$$\delta M \leq 0.05\,\mathrm{mm}, \tag{10}$$

$$\delta t_{\mathrm{shim}} \leq 0.02\,\mathrm{mm}, \tag{11}$$

then with $\delta t_{\mathrm{ring}} = 0.05\,\mathrm{mm}$, the RSS combination gives $\delta h \approx 0.08\,\mathrm{mm}$, compatible with the desired $\pm 0.1\,\mathrm{mm}$ bound around h_0.

To fine-tune the ride height during assembly, shim washers under the readhead (or ground spacers under the ring) can be used while monitoring the encoder's internal signal level and status LED. Once the signal level has been adjusted to the centre of the acceptable range, the resulting ride height can be estimated using the logarithmic formula, yielding an absolute uncertainty of order $\pm 0.02\,\mathrm{mm}$, significantly smaller than the geometric tolerance.

4.4 Radial eccentricity and shaft–ring concentricity

The installation table allows a radial displacement of up to ± 0.5 mm between the readhead arc and the ring. This limit primarily guarantees that the readhead still overlies the magnetised track and that full-period sinusoidal signals are detected. However, any true eccentricity e of the ring relative to the encoder output coordinate system introduces an angle-dependent error. To first order, the resulting error in measured angle can be approximated by

$$\Delta\theta(\varphi) \approx \frac{e}{R}\sin\varphi, \tag{12}$$

where φ is the true rotation angle and $\Delta\theta$ is expressed in radians. The amplitude of the systematic error is therefore approximately

$$\Delta\theta_{\max} \approx \frac{e}{R}. \tag{13}$$

With $R = 32$ mm, several representative values are:

$$e = 0.5\,\text{mm} \Rightarrow \Delta\theta_{\max} \approx 0.895^\circ, \tag{14}$$
$$e = 0.1\,\text{mm} \Rightarrow \Delta\theta_{\max} \approx 0.179^\circ, \tag{15}$$
$$e = 0.05\,\text{mm} \Rightarrow \Delta\theta_{\max} \approx 0.090^\circ, \tag{16}$$
$$e = 0.02\,\text{mm} \Rightarrow \Delta\theta_{\max} \approx 0.036^\circ. \tag{17}$$

To ensure that fixture-induced error is a small fraction of typical IMU errors (often on the order of 0.1° to 1° over short intervals), a practical target is $e \leq 0.05$ mm, and ideally $e \leq 0.02$ mm. This is substantially stricter than the ± 0.5 mm functional tolerance but well aligned with the interference-fit philosophy of the manufacturer.

Concentricity between the ring and the shaft is controlled through:

- The tolerance on the shaft diameter where the ring mounts (e.g. a g6 or h6 shaft with an H7 ring bore).
- The axial runout of the shaft relative to the motor bearings.
- The machining accuracy of any intermediate adapters between the motor hub and the ring.

If the shaft is ground to within 0.01 mm of nominal and axial runout relative to the motor stator is kept below 0.02 mm (TIR), then the combined eccentricity budget can realistically be kept under 0.03 mm, satisfying the stricter design goal.

4.5 Readhead radial and tangential position

The datasheet allows:

- Tangential displacement up to ± 0.3 mm.
- Radial displacement up to ± 0.5 mm for MB064.

These limits have only a weak influence on accuracy compared to true ring eccentricity, as long as the readhead's active area still spans the magnetised track. Nevertheless, the Treexalerator design should aim at significantly better figures to maximise signal quality and leave margin for manufacturing variation and assembly error.

Since the readhead mounting pattern is relatively compact, it is straightforward to define the bolt circle or locating dowel positions with a position tolerance of 0.1 mm. Using reamed dowel holes aligned to the ring centre, the radial offset between readhead arc and ring centre can be kept below 0.05 mm, corresponding to a negligible additional contribution to angular error compared to shaft–ring eccentricity.

4.6 Deck alignment and IMU positioning

The IMU is mounted on the perforated deck, which is tied to both end plates. Misalignment between the deck and the true shaft axis can introduce a difference between the physical rotation axis experienced by the IMU and the angle reported by the encoder. Let β denote the tilt of the deck normal relative to the shaft axis. If the IMU's sensitive axes are aligned using the deck surfaces, any non-zero β will appear as an apparent scale factor error or cross-axis sensitivity.

To keep such effects small, it is desirable to impose:

- Perpendicularity of the deck to the shaft axis better than 0.05 mm over the deck width (corresponding to tilts of order 0.05° for a 60 mm half-width).
- Positioning of the IMU relative to a defined reference hole or edge with a tolerance of 0.05 mm and a rotational alignment of a few tenths of a degree.

These values are readily achievable with standard machining and careful assembly, and they keep IMU alignment errors below the expected sensor bias and noise levels.

5 Recommended Tolerances for the Treexalerator

Table 1 summarises practical tolerance targets for the key mechanical features of the Treexalerator. These numbers are not strict limits from the datasheet; instead they are *design goals* chosen to keep fixture errors comfortably below both the encoder's intrinsic capabilities and the typical IMU error budget.

These recommended values are compatible with a workflow where the main body is 3D printed to provide the overall geometry, and the critical faces and bores are subsequently machined (e.g. on a lathe or mill) to achieve the required accuracy. In particular, the encoder-side plate, the ring seat, and the readhead pad should be treated as precision features, while the outer contours and non-critical holes can remain at 3D-print tolerance levels.

6 Discussion

The analysis above shows that the encoder's formal installation tolerances are comparatively generous, especially in radial and tangential directions. From the perspective of using the encoder as a reference for IMU accuracy testing, simply meeting those limits is insufficient: a ring eccentricity of ± 0.5 mm could induce almost one degree of sinusoidal angle error, which is on the same scale as the errors of many low- and mid-grade IMUs.

By tightening the mechanical design to achieve eccentricities of order 0.02 —-0.05 mm, plate tilts below 0.1°, and ride height controlled within ± 0.1 mm around an optimal setpoint, the Treexalerator can ensure that fixture-induced angle errors are at least a factor of three to ten smaller than the IMU's own errors. This makes it possible to attribute the majority of the observed discrepancy between encoder and IMU to the IMU, not the mechanics.

Moreover, the encoder's self-calibration procedures (provided by the manufacturer) can correct a large fraction of the remaining systematic error due to residual eccentricity and sensor imperfections, further improving its suitability as a reference standard.

7 Conclusions

Starting from the AksIM-2 MB064 encoder datasheet, this report has derived practical mechanical tolerance targets for the Treexalerator test rig. The key conclusions are:

- The datasheet limit of 0.2° for tilt corresponds to about 0.11 mm variation in ride height across the MRA064 ring; designing for half of this variation provides comfortable margin.

- Although the encoder will function with up to ± 0.5 mm radial misalignment, such eccentricities can produce nearly degree-level angle errors. Designing for $\lesssim 0.05$ mm eccentricity is advisable when the encoder acts as a reference.
- Achieving the recommended tolerances is feasible with a combination of 3D printing for bulk geometry and conventional machining for critical faces and bores.

Implementing these tolerances in the Treexalerator drawing, using clear datums and GD&T symbols, will ensure that manufactured parts can be inspected and accepted based on objective criteria, and that the resulting rig is suitable for high-quality IMU characterisation.

References

[1] RLS d.o.o., *AksIM-2 MB Series Magnetic Encoder – Data Sheet MBD01_14*, 2024.

[2] CubeMars, "GL60 KV25 Gimbal Motor," product web page and installation drawing, accessed November 2025.

Table 1: Recommended mechanical tolerances for the Treexalerator fixture.

Feature	Suggested tolerance	Rationale
Parallelism between encoder-side plate and motor-side reference plane	$\leq$ 0.05 mm over ring radius	Ensures tilt $\alpha \lesssim 0.09°$, well inside the 0.2° limit and reduces ride-height variation.
Separation between plates (faces that set ring–readhead distance)	$\pm$0.05 mm	Combined with ring thickness tolerance and shimming, keeps ride height within $h_0 \pm 0.1$ mm and inside the 0.05 mm to 0.35 mm range.
Flatness of each plate face (where ring and readhead mount)	$\leq$ 0.03 mm	Minimises local deviations in ride height and improves contact between PCBs / spacers and the structure.
Shaft diameter where ring seats	match ring bore (e.g. shaft h6 or g6 vs. ring H7)	Achieves radial clearance $\lesssim$ 0.02 mm, consistent with press-fit recommendations in the datasheet for smaller rings.
Radial runout (TIR) of ring relative to shaft axis	$\leq$ 0.02 mm	Limits eccentricity-induced angular error to $\Delta\theta_{\max} \lesssim 0.036°$.
Readhead mounting pad height	controlled such that overall ride height within $h_0 \pm 0.1$ mm	Achieved via precise machining of the pad and shimming.
Radial position of readhead	$\pm$0.1 mm relative to ring centre	Much better than the $\pm$0.5 mm functional limit; keeps magnetic field conditions uniform.
Tangential position of readhead	$\pm$0.1 mm along ring circumference	Better than the $\pm$0.3 mm limit and easy to achieve with dowel pins or precise hole patterns.
Perpendicularity of deck to shaft axis	$\leq$ 0.05 mm over deck width	Keeps IMU rotation axis close to encoder axis, minimising kinematic error.
Motor pilot / GL60 locating features	radial clearance $\leq$ 0.03 mm, face runout $\leq$ 0.02 mm	Ensures the motor shaft is coaxial with the fixture datums so that any residual eccentricity is dominated by ring mounting, not motor mounting.