Optimizing Astronomical Imaging System Alignment Through Spatial PSF Analysis and Physics-Based Aberration Modelling

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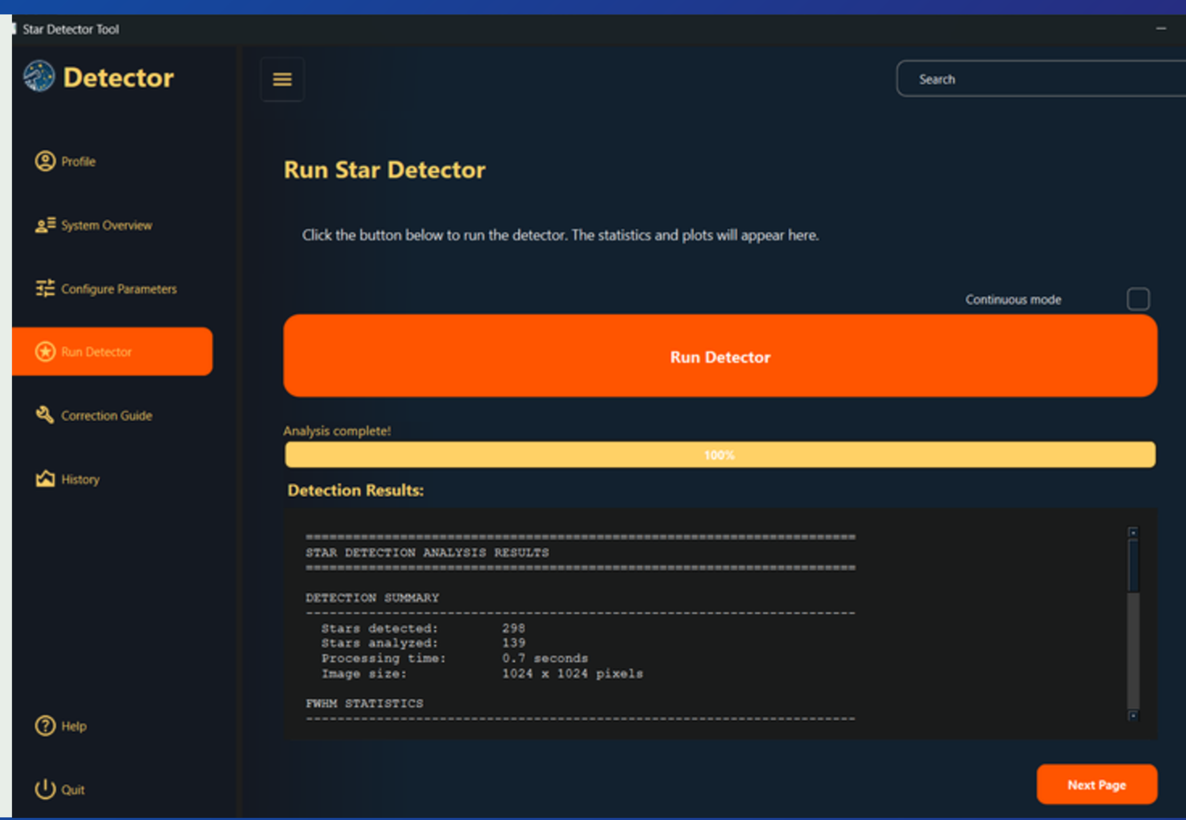
1. INTRODUCTION

- **The Problem**: Atmospheric, optical, and mechanical distortions (such as sensor tilt, field curvature, coma, and astigmatism) degrade the Point Spread Function (PSF). Lots of research has gone into recovering it but information lost at capture stage cannot be recovered.
- **The Solution**: A hardware-first approach that corrects mechanical alignment at the source before exposure, rather than relying solely on post-processing. It aims to minimise error sources to ease future PSF modelling steps.



- **Astronomical images are degraded by atmospheric, optical, and mechanical distortions — we correct mechanical alignment at the source before image is captured, rather than relying only on post-processing.**
- **The tool detects stars across the field and measures FWHM and ellipticity for each source via second-moment analysis.**
- **We visualise the data in many forms to showcase the distortions, such as through a 3D ellipticity map, sensor tilt and field curvature plot etc.**
- **Fitted parameters are converted to physical corrections: shim heights at each mounting screw, sensor tilt angle and direction, backfocus adjustment, and focal surface curvature radius.**

2. METHODS

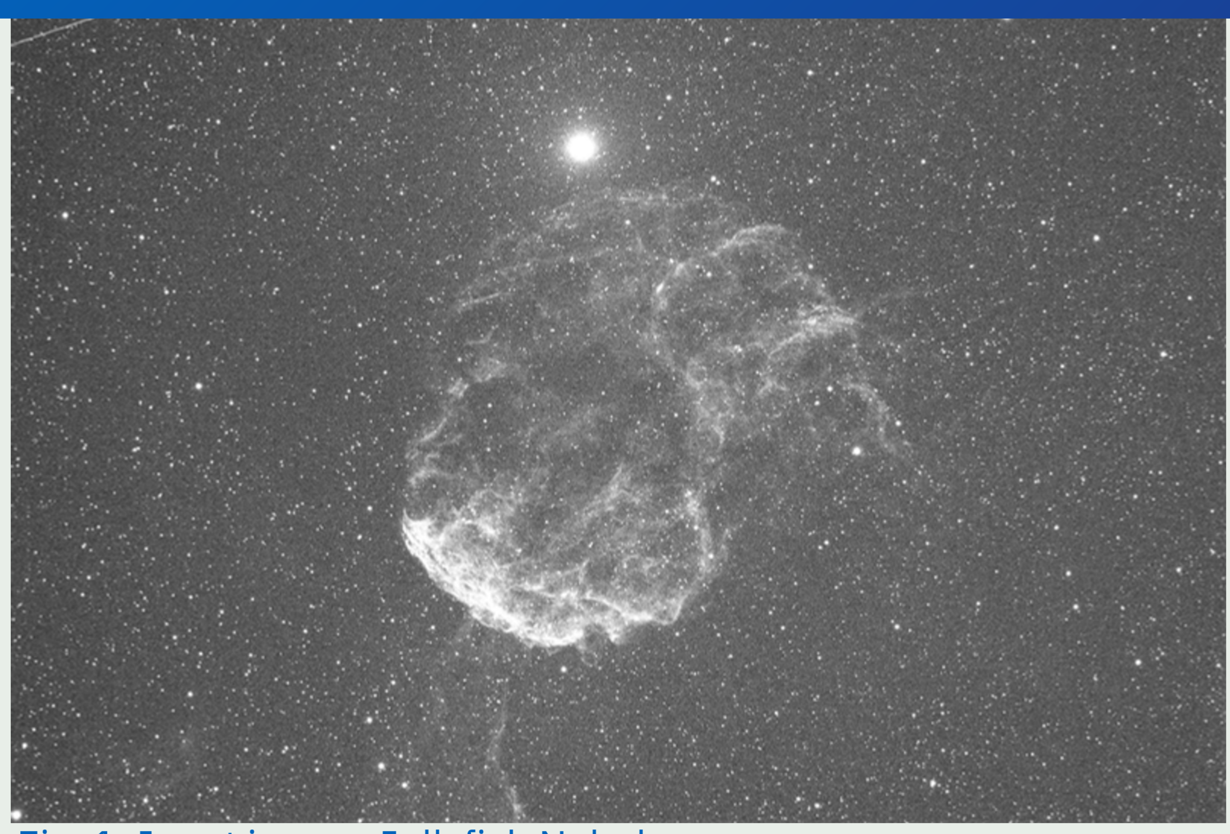


Fig. 1: Input image: Jellyfish Nebula

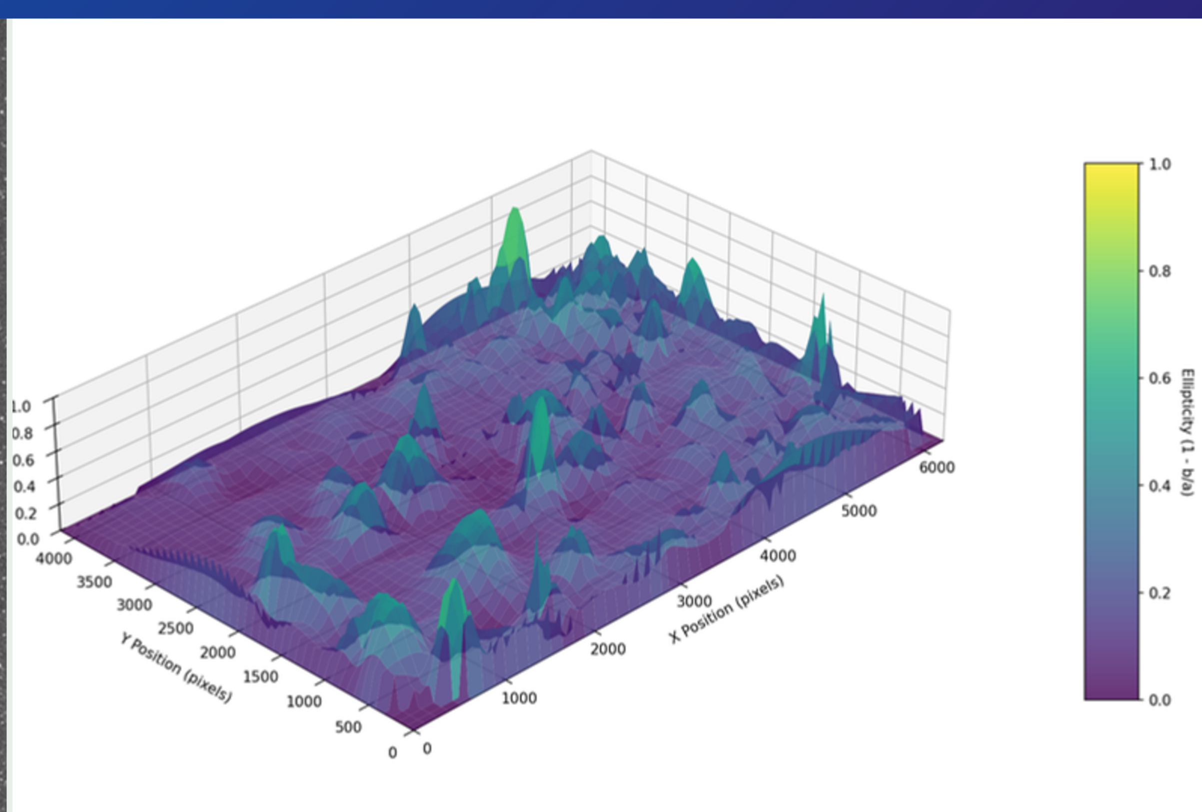


Fig. 2: Ellipticity distribution 3D view

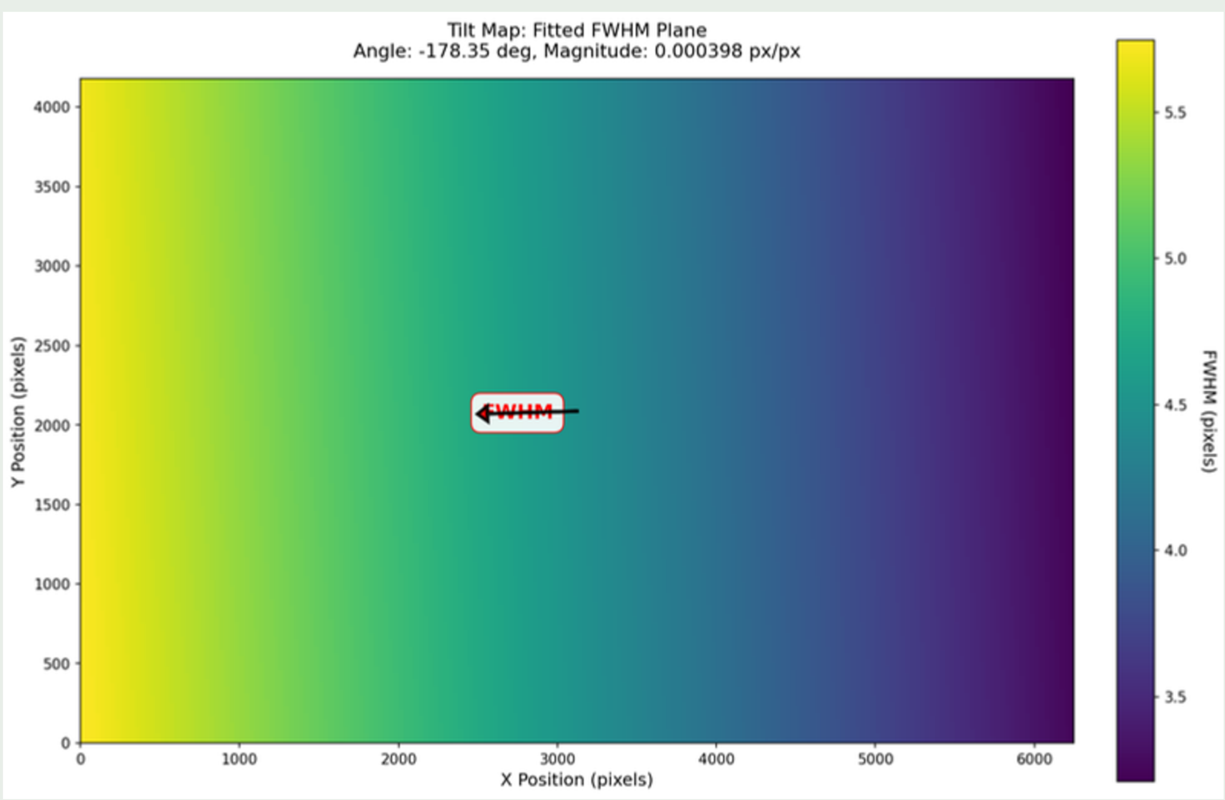


Fig. 3: Sensor tilt gradient and direction

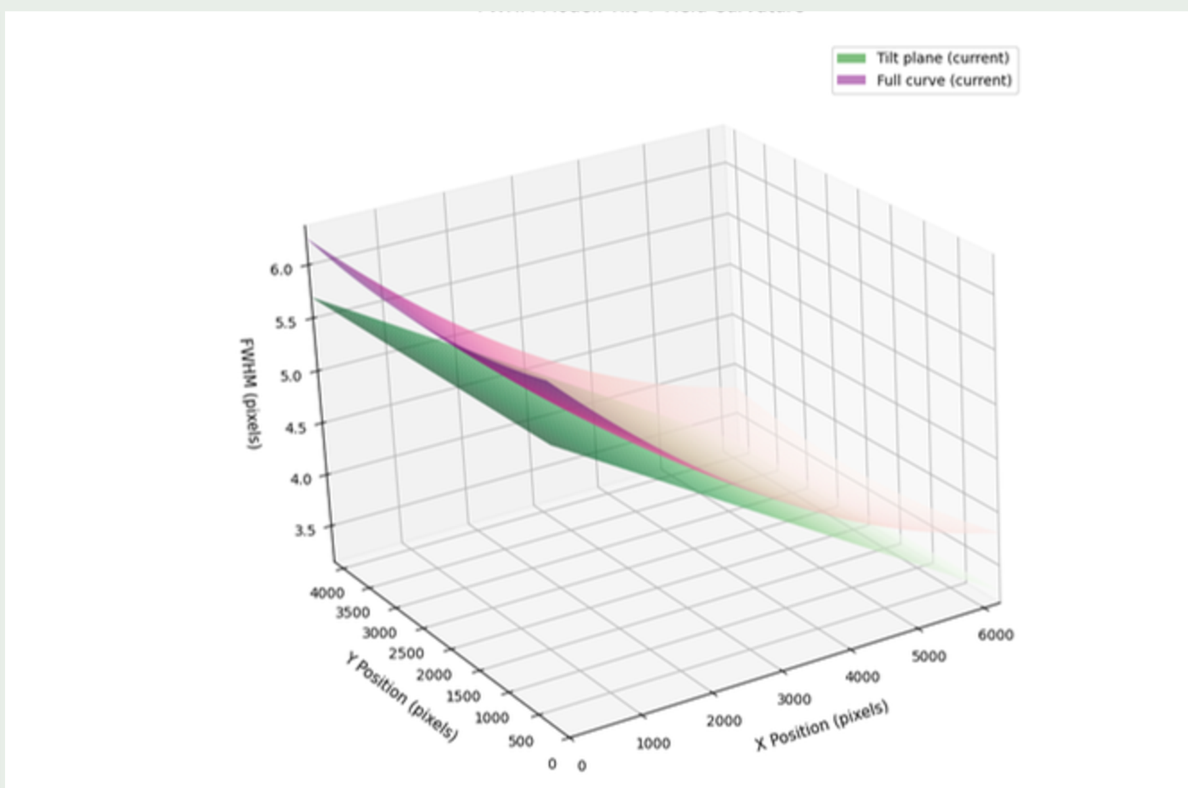


Fig. 4: Sensor tilt and Curvature of Field

- Detect stars at multiple FWHM scales, filter by SNR, sharpness, roundness, and brightness.
- Measure FWHM and ellipticity from intensity-weighted second moments within a circular aperture.

$$\sigma_a = \sqrt{\lambda_1}$$
$$\sigma_\beta = \sqrt{\lambda_2}$$
$$\mathbf{FWHM = 2.355 \times \sigma}$$
$$\mathbf{e = 1 - b/a}$$

- Fit a parametric model to separate the linear tilt gradient from radial field curvature.

$$\mathbf{FWHM(x, y) = a \cdot x + b \cdot y + c + d \cdot r^2}$$

- Convert the tilt coefficients to physical defocus and sensor tilt angle.

$$g = p \cdot \sqrt{\hat{a}^2 + \hat{b}^2}$$
$$\Delta z = N \cdot g \cdot \sqrt{W^2 + H^2}$$
$$\alpha \approx \Delta z \,/\, \text{sensor diagonal}$$

- Project the defocus gradient onto each mounting screw to obtain shim corrections.

$$g_x = N \cdot \hat{a} \cdot 1000/p$$
$$g_y = N \cdot \hat{b} \cdot 1000/p$$
$$\mathbf{\Delta z_i = g_x \cdot x_i + g_y \cdot y_i}$$

3. CORRECTIONS

From the parametric model fit, we calculate how each screw on the mount can be adjusted to fix the sensor tilt present. The corrections are presented as such:

SHIM CORRECTIONS

Screw 1 at (-11.75, 7.85): -23.13 μm (shifted: 0.91 μm)
Screw 2 at (11.75, 7.85): 24.04 μm (shifted: 48.08 μm)
Screw 3 at (-11.75, -7.85): -24.04 μm (shifted: 0.00 μm)
Screw 4 at (11.75, -7.85): 23.13 μm (shifted: 47.17 μm)
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4. PHYSICS-BASED SIMULATOR

The observed stellar image is constructed by convolving a point source with three independent PSF components and adding noise.

I_star = I_source ∗ PSF_atm ∗ PSF_tel ∗ PSF_track + noise

1. The atmospheric PSF is a Moffat profile parameterised by FWHM and wing steepness β.
The Moffat function captures the extended wings of long-exposure atmospheric PSFs more accurately than a Gaussian. Lower β produces broader wings consistent with turbulence; high β approaches a Gaussian.

2. The telescope PSF is built from a Zernike wavefront error surface propagated through Fourier optics. Zernike polynomials form an orthogonal basis over the circular aperture, with each term mapping to a specific aberration: tilt (Z_2, Z_3), defocus (Z_4), astigmatism (Z_5, Z_6), coma (Z_7, Z_8).

3. The tracking kernel models mount drift as a rectangular function along the error direction. During long exposures, uncorrected mount drift displaces the stellar image at a constant rate, producing a uniform elongation along the drift angle θ.

4. Additive white Gaussian noise is applied independently of the PSF, allowing SNR to be swept separately. This separation isolates the effect of noise on parameter recovery from the underlying distortion content.

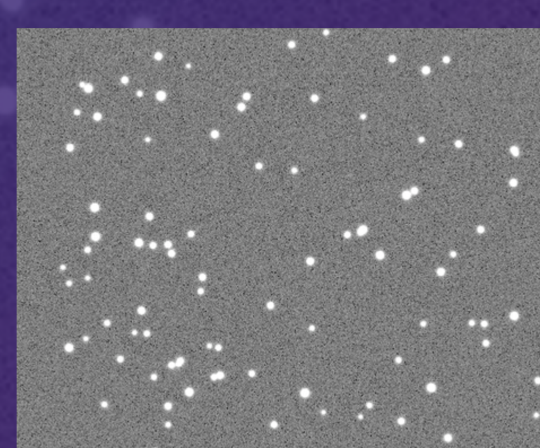
Fig. 5: Section of output from physics-based stellar image simulator

5. REFERENCES

- Liaudat et al. Frontiers in Astronomy and Space Sciences 2023, DOI={10.3389/fspas.2023.1158213}
- Liu et al. The Astrophysical Journal 2022, DOI={10.3847/1538-4357/ac32c6}

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