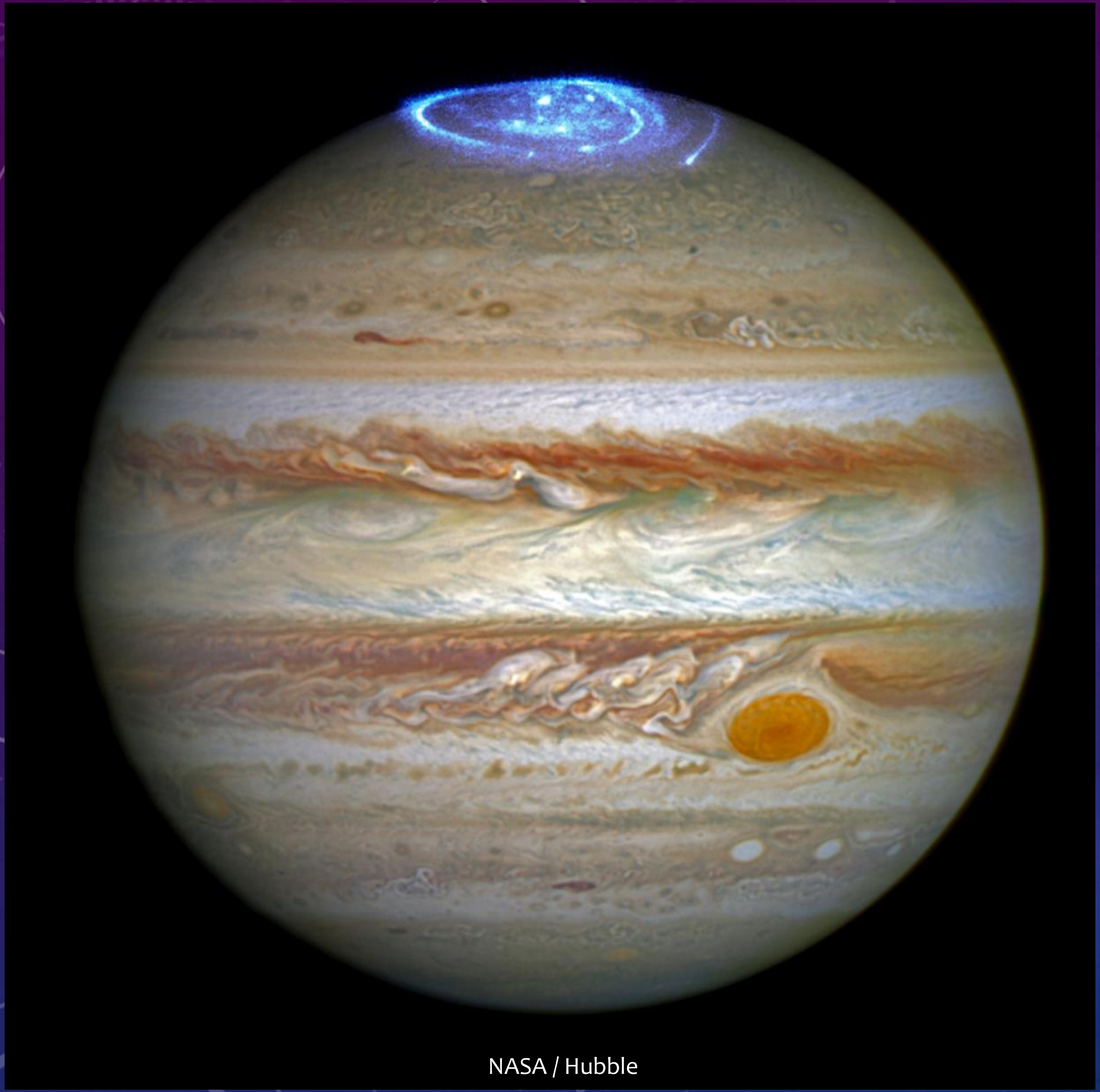
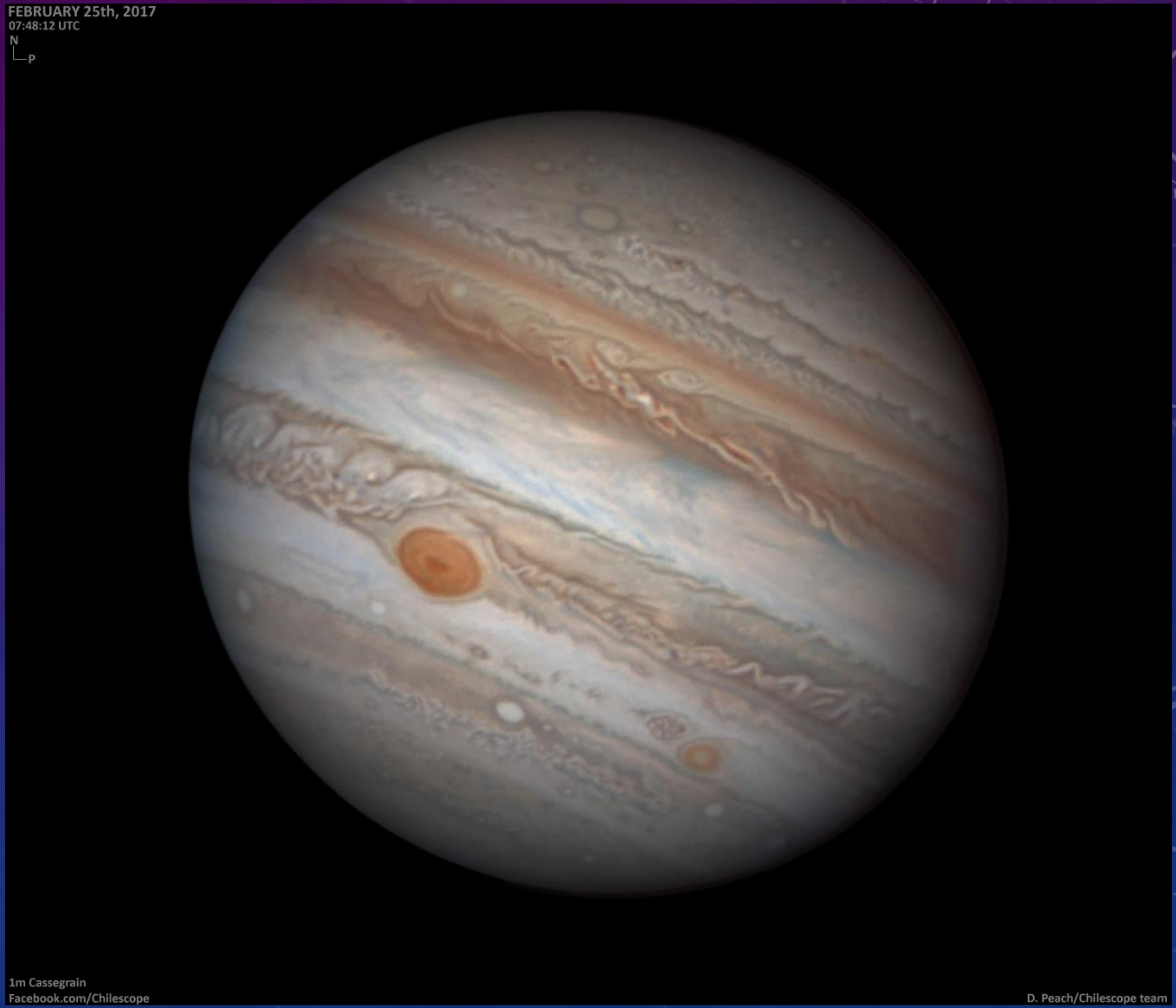

NASA / Hubble

# HIGH RESOLUTION PLANETARY IMAGING

PATRICK HSIEH

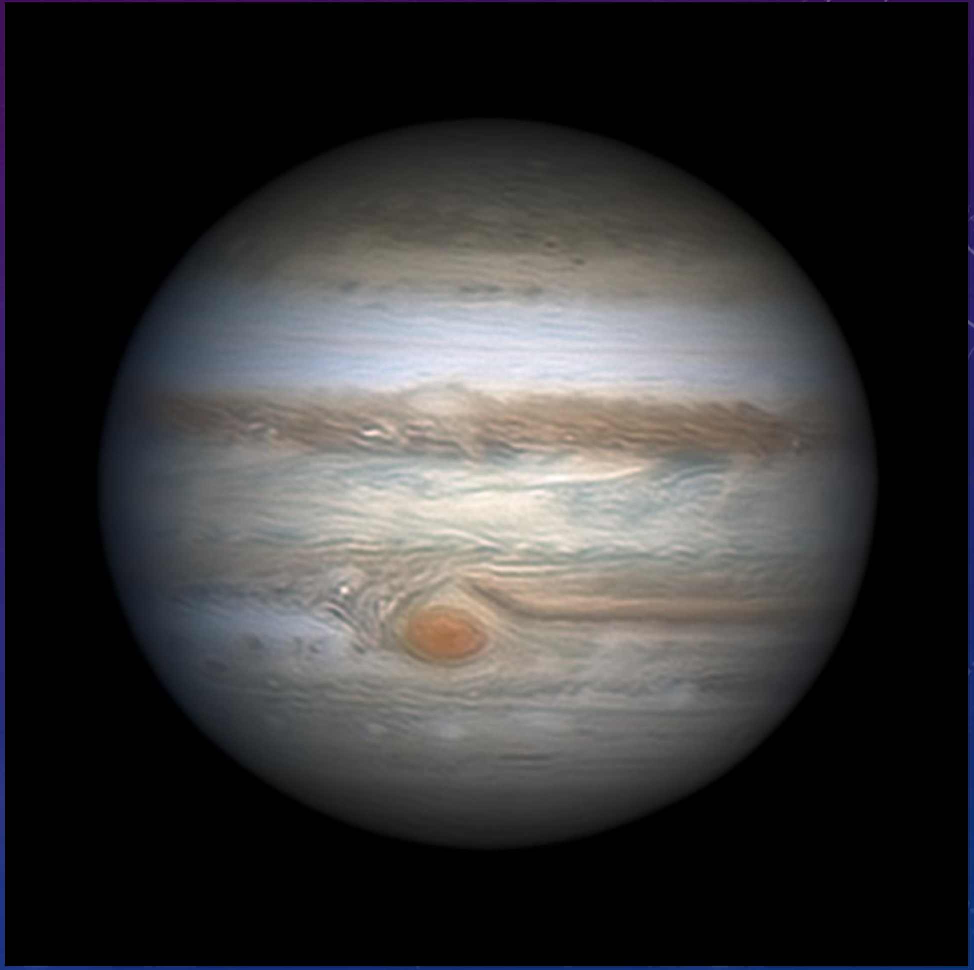
# OVERVIEW

- The Objective
- The Challenges
- Fundamental Principles
- Equipment Selection
- Imaging Technique
- Processing



# THE OBJECTIVE

- Highest resolution images possible of planetary bodies
  - Maximum achievable resolution
  - Sources of image degradation
  - Countermeasures

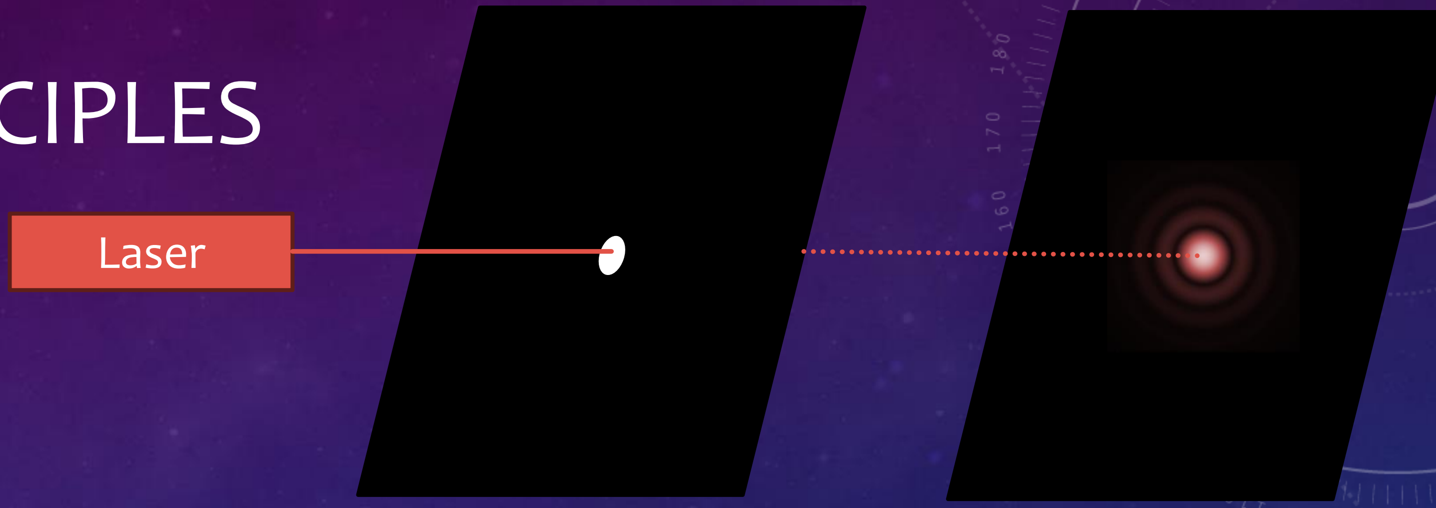


# THE CHALLENGES

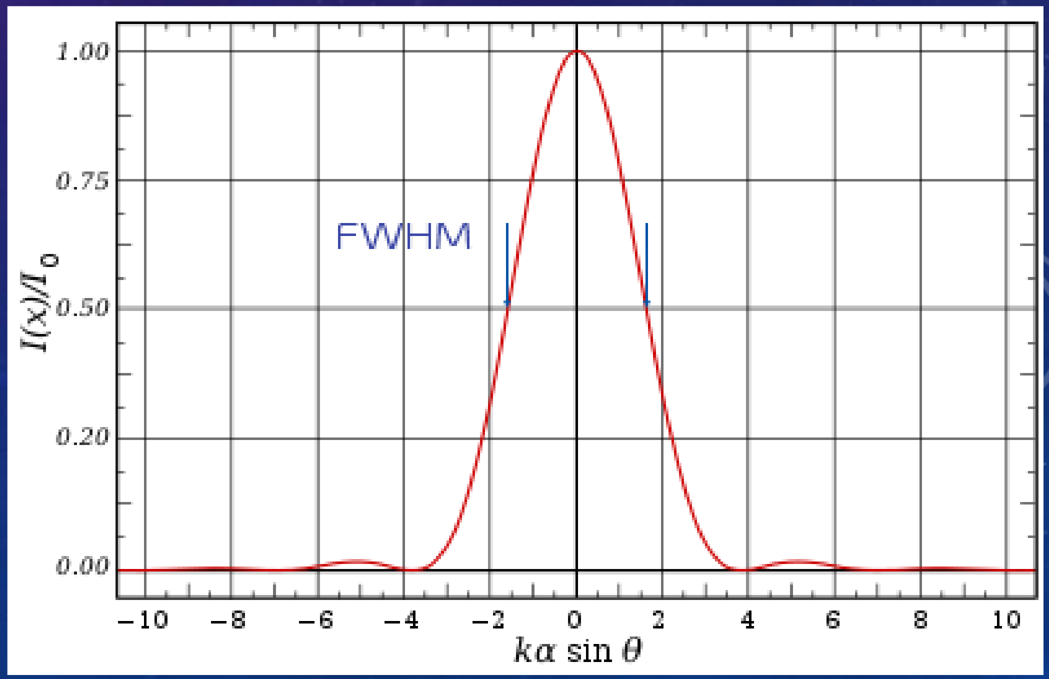
- Targets are small
  - Need to understand equipment factors to maximize resolution of details
- Imaging through 30+ miles of moving air
  - You cannot ever do better than Mother Nature presents in front of the telescope
  - Different countermeasures for near, middle, and distant atmospheric ranges
  - Mathematical countermeasures

# FUNDAMENTAL PRINCIPLES

(ACHIEVABLE RESOLUTION)




- Behavior of light
  - Wave-particle duality
  - Airy disk
    - Size determined by:
    - Wavelength of light (λ)
      - Red ≈ 650 nm, green ≈ 550 nm, blue ≈ 450 nm
    - Aperture (d)
      - Larger aperture yields smaller disk = higher resolution
    - Focal length (L)
      - Longer focal length yields larger disk = more magnification

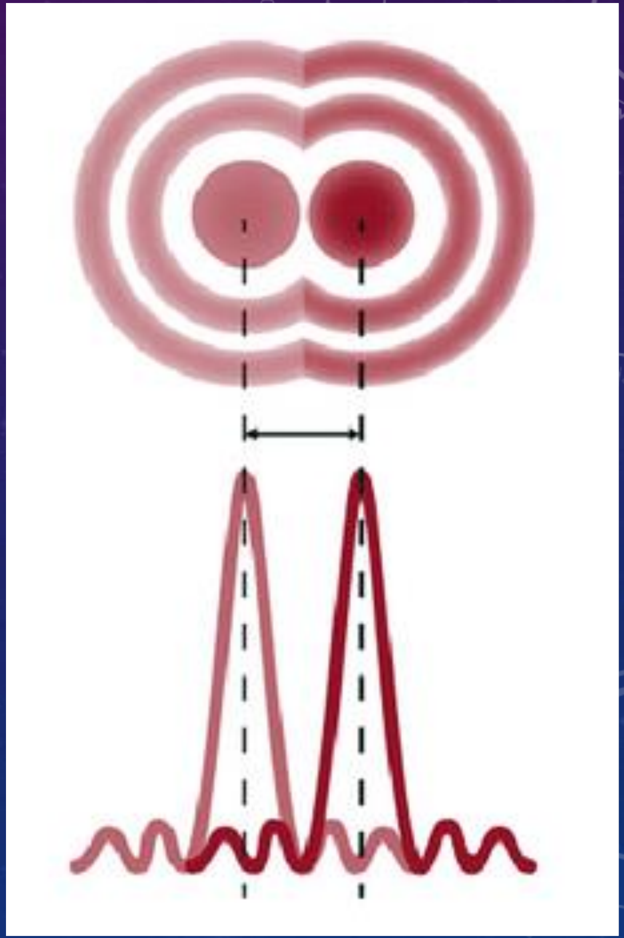



✓ TL;DR : Maximum Achievable Resolution
  - Angular resolution depends ONLY on aperture
  - Linear resolution depends ONLY on f ratio

# FUNDAMENTAL PRINCIPLES

(ACHIEVABLE RESOLUTION)

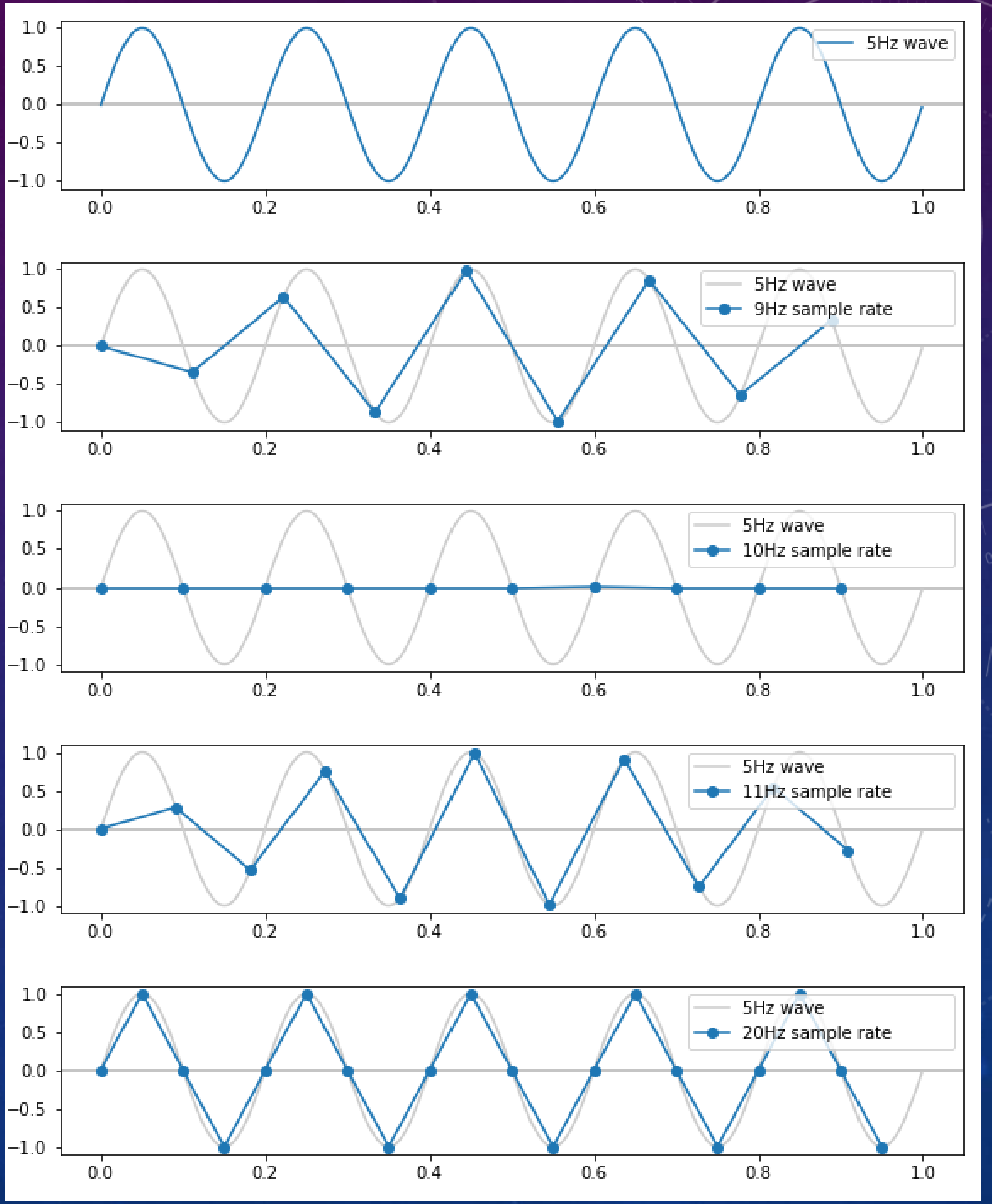
- Resolution
  - Expressed as an angle
    - 360 degrees in a circle, 60 arcminutes per degree, 60 arcseconds per arcminute
    - 5° (5 degrees), 5' (5 arcminutes), 5" (5 arcseconds)
  - Ability to resolve determined by distance between peaks of Airy disks
  - Rayleigh limit = peak of one spot at first minimum of second
    - RL = 0.61 x λ / d, i.e. half diameter of Airy disk
    - 138 / aperture (mm) = arcseconds
  - Dawes limit = separation where two spots visually distinguishable
    - Close to FWHM of Airy disk
    - 116 / aperture (mm) = arcseconds
- **TL;DR : maximum theoretical (diffraction limited) resolution Dawes Limit or FWHM of Airy disk**



# FUNDAMENTAL PRINCIPLES

(ACHIEVABLE RESOLUTION)

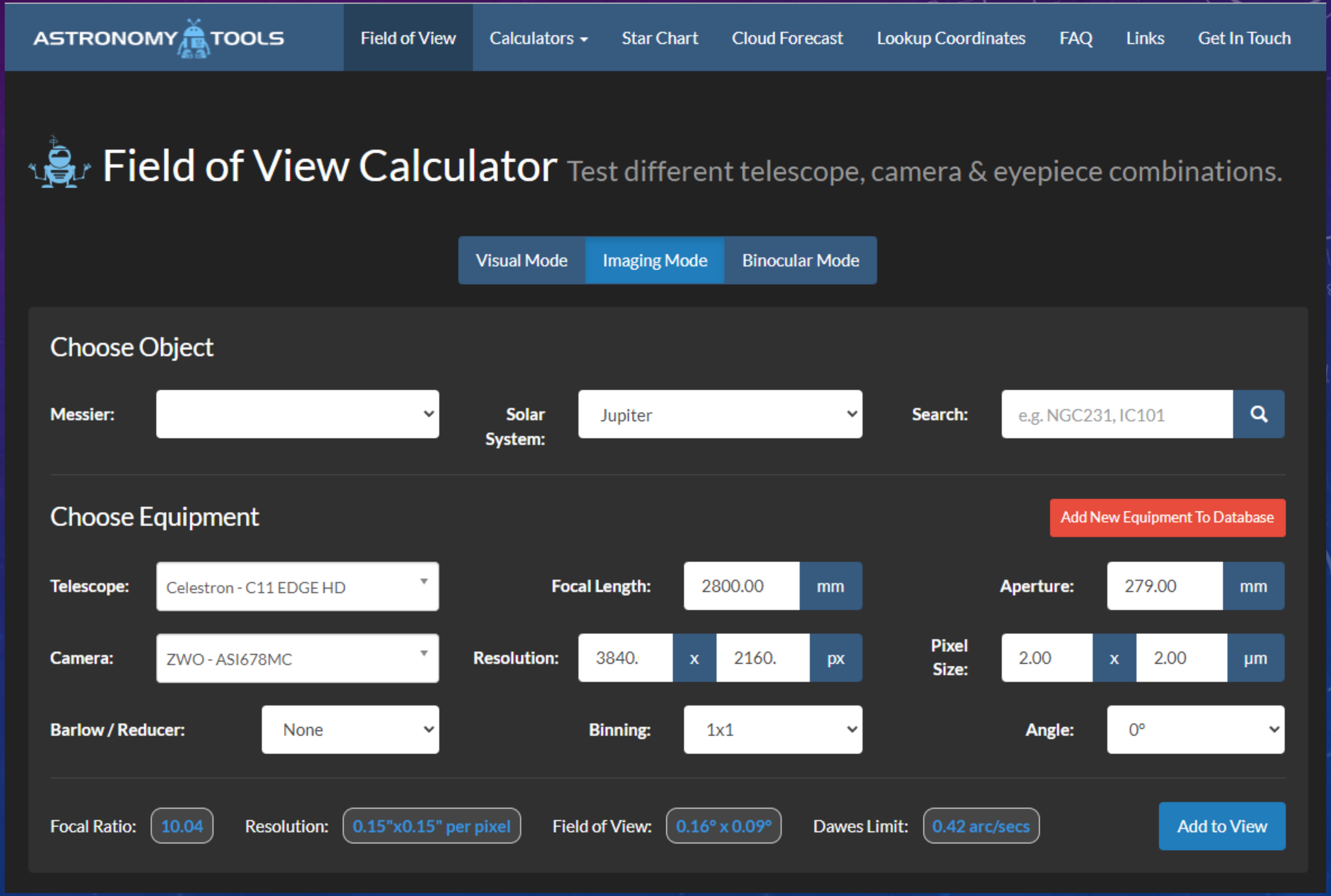
- Sampling
  - How many data points do we need to accurately reproduce a feature?
  - Nyquist criteria
    - At least 2 samples per feature = "Optimal" sampling
    - "Undersampling" – sacrifices detail
    - "Oversampling" – sacrifices signal-to-noise ratio
  - Optimize based on
    - Dawes limit
      - ≥ 2 pixels per Dawes limit
    - Pixels per Airy disk
      - ≥ 6 pixels per Airy disk



# FUNDAMENTAL PRINCIPLES

(ACHIEVABLE RESOLUTION)

- Based on Dawes Limit
  - Calculate scope limit
  - Calculate pixel angular resolution
    - Pixel Size (µ) · FL (mm) · 206.265
  - ≥ 2 pixels per Dawes Limit




https://astronomy.tools

# FUNDAMENTAL PRINCIPLES

(ACHIEVABLE RESOLUTION)

- Based on Pixels per Airy Disk
  - ≥ 6 pixels per full Airy disk

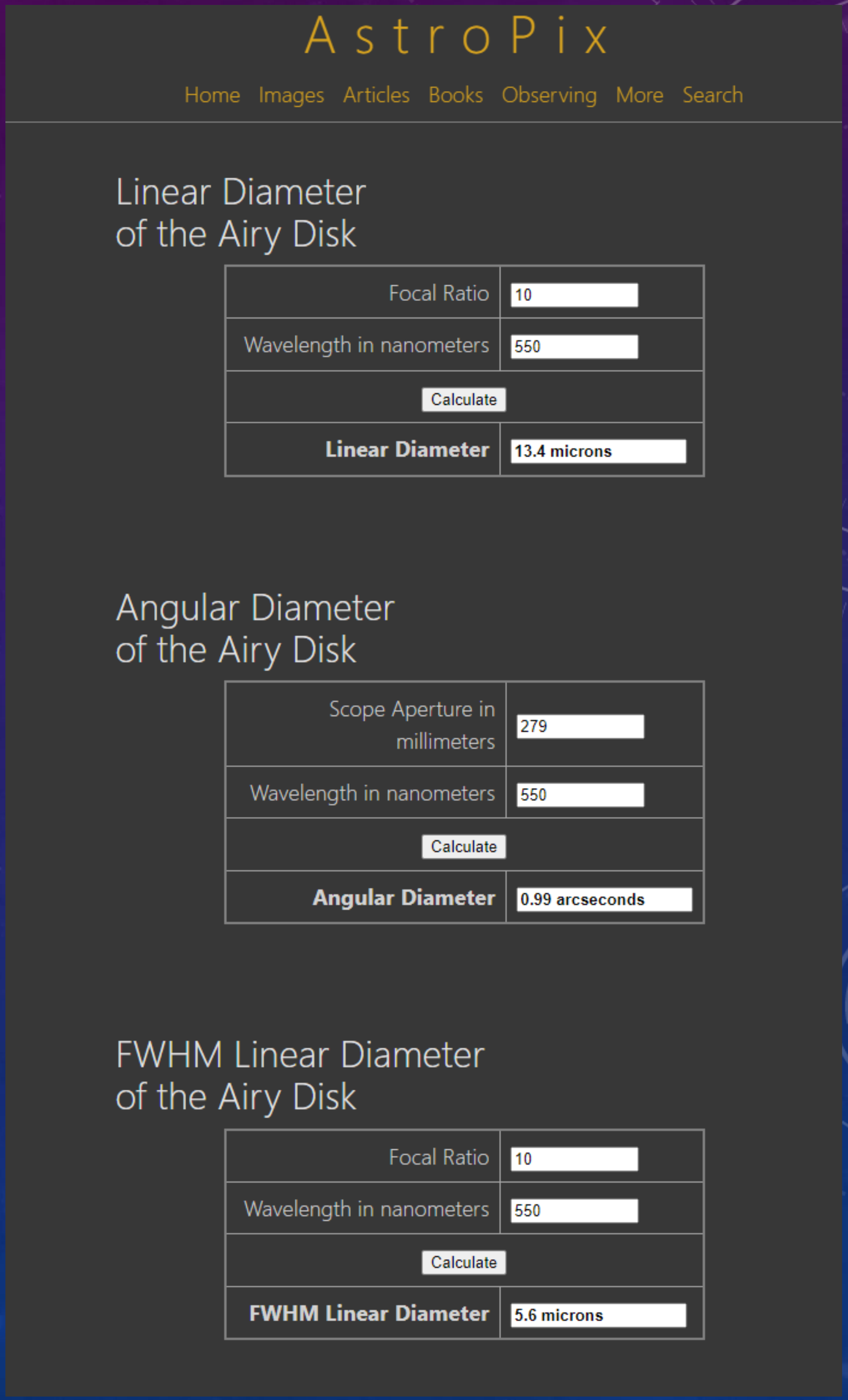
    or

  - ≥ 2 pixels per FWHM Airy disk

✓ TL;DR : Optimize sampling

  - ≥ 2 pixels per Dawes or
    ≥ 6 pixels per Airy disk
  - 3.76 µ pixels -> ~f/20
  - 2 µ pixels (ASI 678MC) -> ~f/10

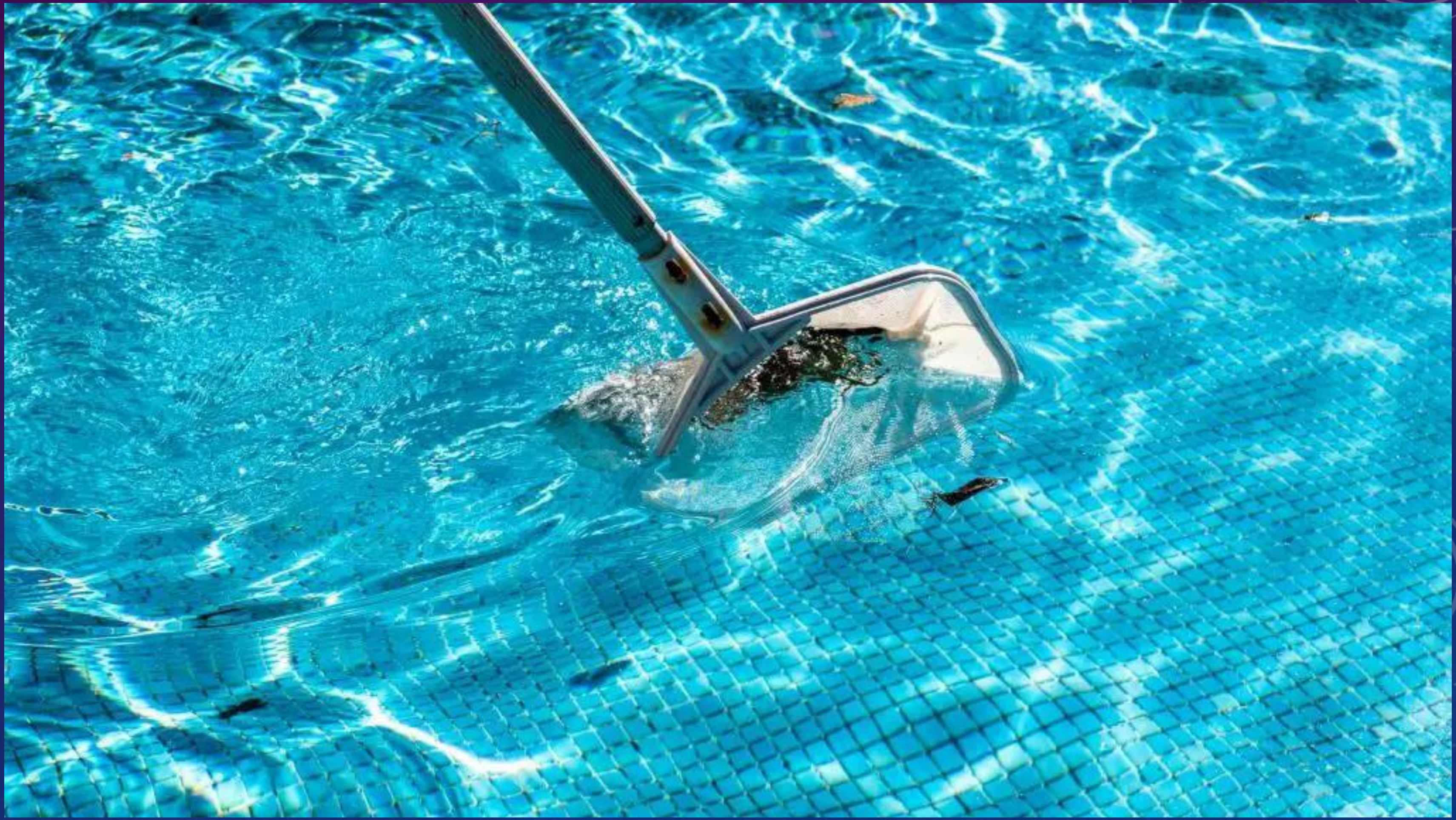
https://www.astropix.com/html/astrophotography/astrophotography-calculators.html



# FUNDAMENTAL PRINCIPLES

(IMAGE DEGRADATION)

- Air turbulence produces distortion
  - Wind speed (at all levels)
  - Temperature
  - Humidity
  - Local factors
- Image effects depend on
  - Angular resolution
  - Exposure length
  - Limits achievable resolution, regardless of instrument capability



# FUNDAMENTAL PRINCIPLES

(ACHIEVABLE RESOLUTION)

- Astronomical seeing
  - Smallest feature resolvable due to blurring by atmo
  - Stack images of centroid of star's Airy disk
  - True random turbulence -> Gaussian distribution
    - FWHM of Gaussian peak = seeing
    - "Good" seeing ≈ 1-2"
  - Typically measured over time periods >> 10ms so measured values not necessarily useful for lucky imaging

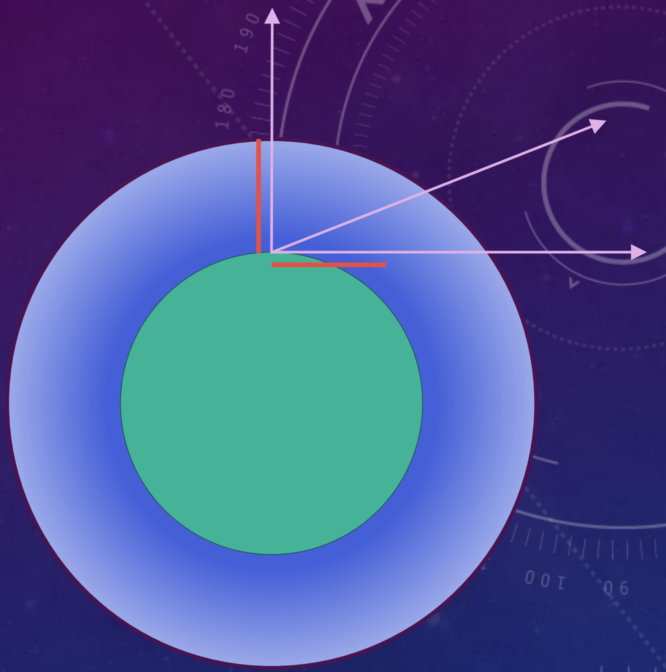
✓ **TL;DR : practically achievable resolution will be no better than seeing conditions at the relevant time-scale**

| | Clouds | | | | Index | | | Bad Layers | | | Ground | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | Low | Mid | High | Arc Sec. | 1 | 2 | Jet Stream | Bot (km) | Top (km) | K/100m | Temp | Rel. Hum. | Celestial Bodies |
| **Sat** 2023-10-07 sunrise: 06:39 sunset: 18:18 moonrise: 00:00 moonset: 15:08 moonphase: 41% | | | | | | | | | | | | | |
| 5 | 0 | 0 | 0 | 0.70 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 69 °F | 23% | L-V-J-UN- |
| 6 | 0 | 0 | 0 | 0.69 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 70 °F | 24% | L-V-J-U-- |
| 7 | 0 | 0 | 0 | 0.69 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 71 °F | 25% | LMV-J-U-- |
| 8 | 0 | 0 | 0 | 0.70 | 5 | 5 | 9 m/s | 01.5 | 02.0 | 0.5 K | 73 °F | 26% | LMV-J-U-- |
| 9 | 0 | 0 | 0 | 0.70 | 5 | 5 | 9 m/s | 01.5 | 02.1 | 0.6 K | 77 °F | 27% | LMVM--U-- |
| 10 | 0 | 0 | 0 | 0.71 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 82 °F | 25% | LMVM----- |
| 11 | 0 | 0 | 0 | 0.72 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 87 °F | 22% | LMVM----- |
| 12 | 0 | 0 | 0 | 0.72 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 89 °F | 20% | LMVM----- |
| 13 | 0 | 0 | 0 | 0.72 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 90 °F | 18% | LMVM----- |
| 14 | 0 | 0 | 0 | 0.71 | 5 | 5 | 8 m/s | 00.0 | 00.0 | 0.0 K | 90 °F | 17% | LMVM----- |
| 15 | 0 | 0 | 0 | 0.68 | 5 | 5 | 8 m/s | 00.0 | 00.0 | 0.0 K | 90 °F | 15% | -MVM----- |
| 16 | 0 | 0 | 0 | 0.64 | 5 | 5 | 8 m/s | 00.0 | 00.0 | 0.0 K | 88 °F | 14% | -M-M----P |
| 17 | 0 | 0 | 0 | 0.62 | 5 | 5 | 9 m/s | 00.0 | 00.0 | 0.0 K | 87 °F | 14% | -M-M-S--P |
| 18 | 0 | 0 | 0 | 0.61 | 5 | 5 | 10 m/s | 00.0 | 00.0 | 0.0 K | 85 °F | 15% | ---M-S-NP |
| 19 | 0 | 0 | 0 | 0.61 | 5 | 5 | 10 m/s | 00.0 | 00.0 | 0.0 K | 82 °F | 15% | -----S-NP |
| 20 | 0 | 0 | 0 | 0.60 | 5 | 5 | 11 m/s | 00.0 | 00.0 | 0.0 K | 79 °F | 16% | ----JS-NP |
| 21 | 0 | 0 | 0 | 0.60 | 5 | 5 | 11 m/s | 00.0 | 00.0 | 0.0 K | 78 °F | 16% | ----JSUNP |
| 22 | 0 | 0 | 0 | 0.60 | 5 | 5 | 11 m/s | 00.0 | 00.0 | 0.0 K | 76 °F | 16% | ----JSUNP |
| 23 | 0 | 0 | 0 | 0.60 | 5 | 5 | 11 m/s | 00.0 | 00.0 | 0.0 K | 75 °F | 17% | ----JSUNP |

https://www.meteoblue.com/en/weather/outdoorsports/seeing/36.292N-115.311E861_America%2FLos_Angeles

# FUNDAMENTAL PRINCIPLES

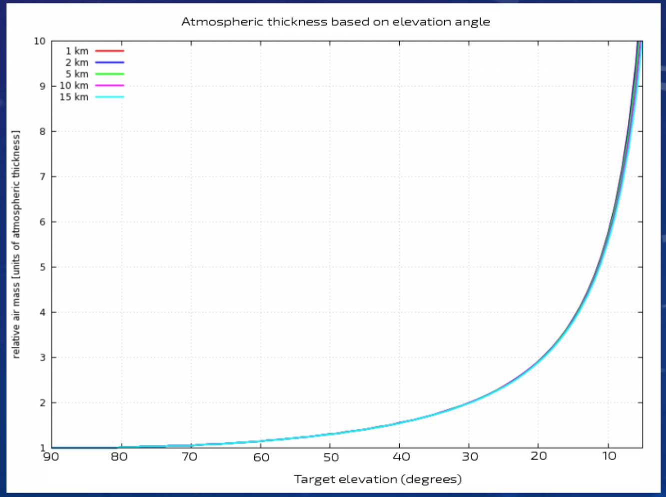
(IMAGE DEGRADATION)



- Ranges of air turbulence
  - Distant (atmospheric)
  - Mid (adjacent surroundings)
  - Near (within scope)
- Distant
  - For AVERAGE conditions, exposures under 7-10 ms have decent chance of stable seeing
    - Shorter is better, assuming equipment and target brightness permit
  - Image through as little air as possible

✓ TL;DR : Countermeasure (distant)

- "Lucky" imaging - high frame rate / short exposure video
- High altitude location
- High target elevation (transit)



# FUNDAMENTAL PRINCIPLES

(IMAGE DEGRADATION)

- Mid – adjacent surroundings
    - Thermal plumes – avoid imaging over blacktop, air conditioning vents, rooftops, etc.
    - Turbulent air – avoid geographic features that channel or disrupt air – hills, canyons, etc.
    - Best - over water

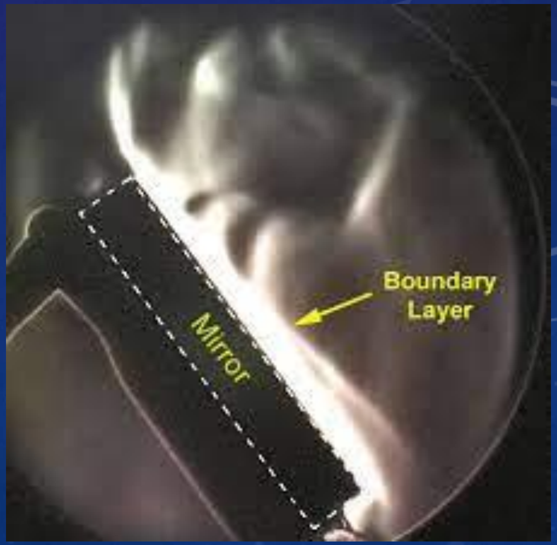
✓ TL;DR : Countermeasures (mid)

- Avoid local terrain conducive to thermals and turbulent air

# FUNDAMENTAL PRINCIPLES

(IMAGE DEGRADATION)


- Near (telescope)
  - Thermal equilibrium is a myth
    - Thermal mass of mirrors and large/heavy tubes will always lag ambient temp, resulting in boundary layer thermal plumes
  - Minimize thermal gradients / plumes within OTA
    - Strategy #1: keep everything inside tube at same temp, minimize temp changes
      - Closed tube scopes, e.g. SCT, Maksutov-Cass, Maksutov-Newt
    - Strategy #2: keep everything inside tube as close to ambient as possible
      - Open tubes better, e.g. Newtonian, open truss designs
      - Thinner tubes better, e.g. refractors
  - Eliminate / minimize boundary layer



# FUNDAMENTAL PRINCIPLES

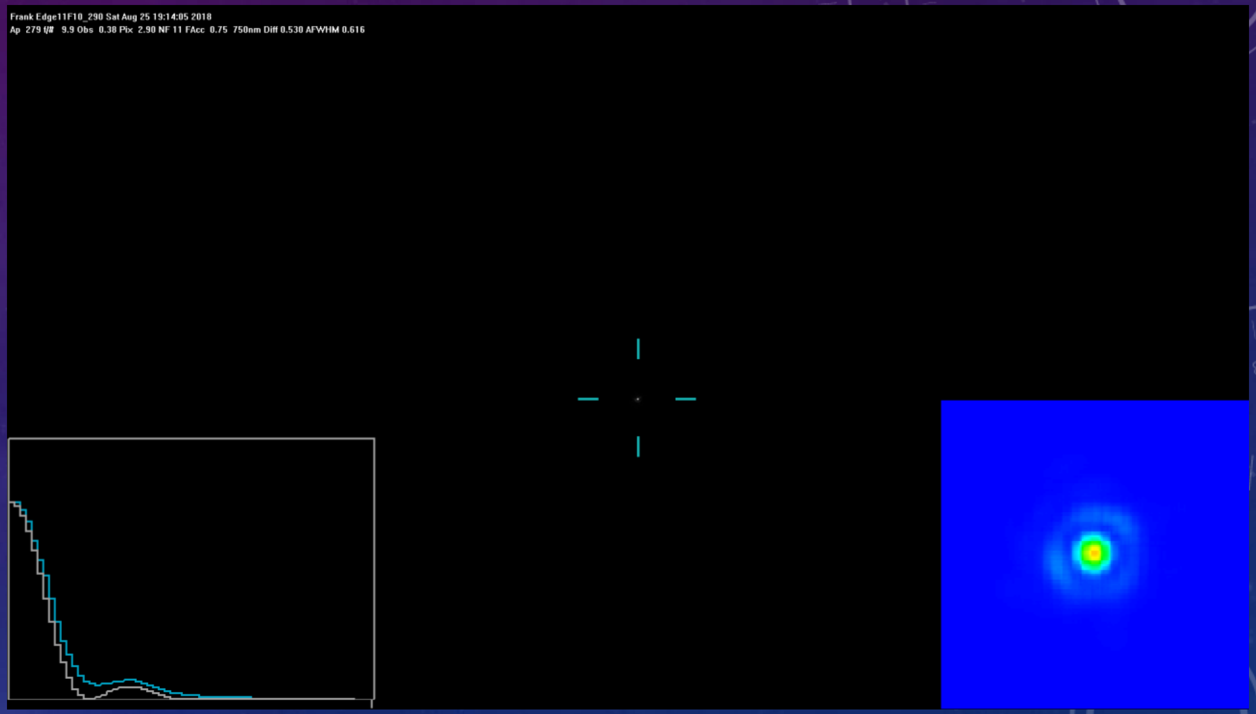
(IMAGE DEGRADATION)

- Closed tube OTAs
  - INSULATE tube
    - 2 layers of Reflectix
    - Can also use neoprene, closed cell foam, etc.
  - No dew shield
    - Minimize boundary layer of corrector plate
- Open tube OTAs
  - Active cooling for mirror
  - Boundary layer fan
  - Focuser / camera on bottom

✓ TL;DR : Countermeasures (near)
  - insulate closed tubes
  - cool open tubes + boundary layer fan

# FUNDAMENTAL PRINCIPLES
## (COLLIMATION)

- Collimation
  - Absolutely critical for scopes that need it – SCT, Newtonian, Maksutov-Cassegrains, etc.
  - Preferably immediately before imaging, at target elevation
  - Lock movable mirrors if possible
  - Use external focuser if possible for SCTs
  - MetaGuide
    - Only collimation method that actually examines the Airy disk
    - Live stacks Airy disk to help deal with seeing




MetaGuide Intro and Download (smallstarspot.com)

# EQUIPMENT SELECTION

- Scope
- Optical train / camera
- Mount / tripod
- Computer

# EQUIPMENT SELECTION (SCOPE)

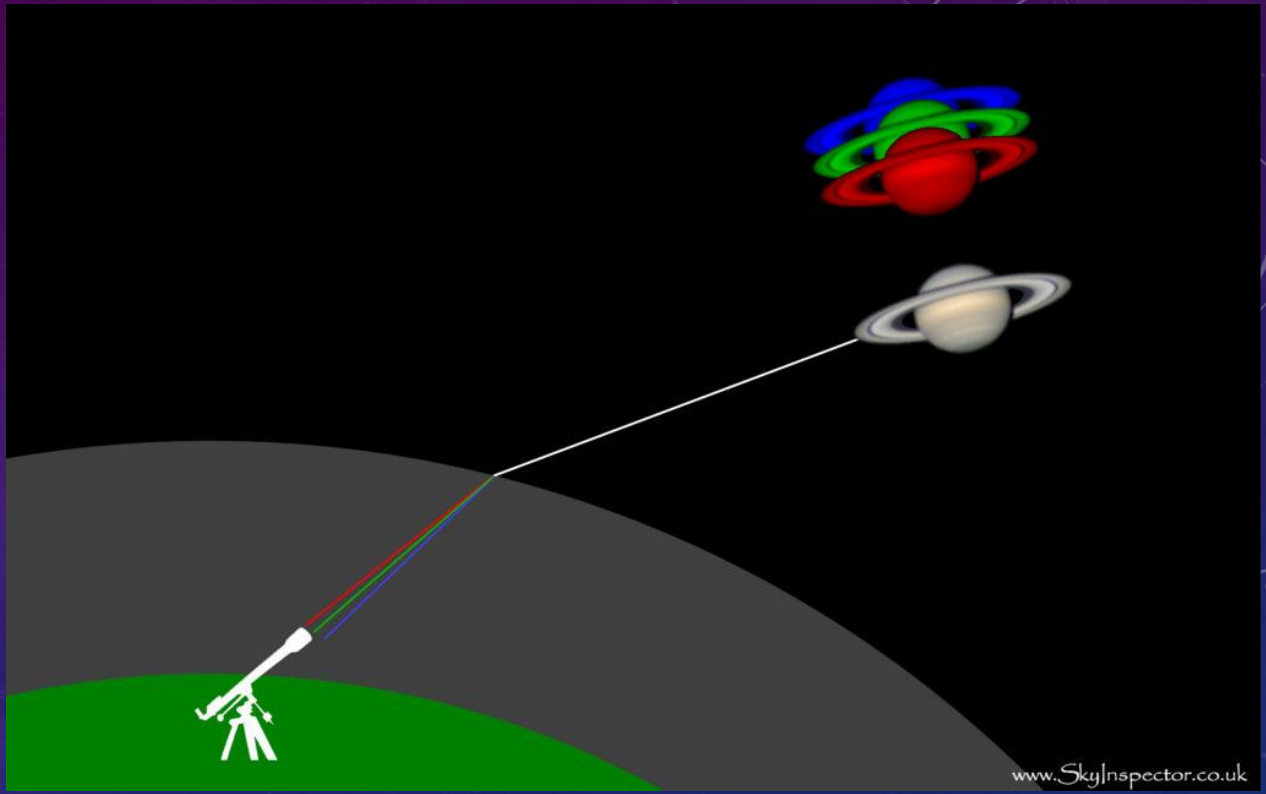
- Detail limited by aperture -> large aperture
- Planets are small -> long focal length
- Thermal stability -> prefer closed tube

| | Aperture | Focal length | Closed tube | Notes |
|---|---|---|---|---|
| SCT | ✓ | ✓ | ✓ | Prefer locked mirror, lower contrast due to central obstruction |
| Mak-Cass | ✗ | ✓ | ✓ | Smaller central obstruction than SCT |
| Newtonian | ✓ | ✗ | ✗ | Must collimate each time |
| Refractor | ✗ | ✗ | ✓ | High contrast, unwieldy at long focal length |

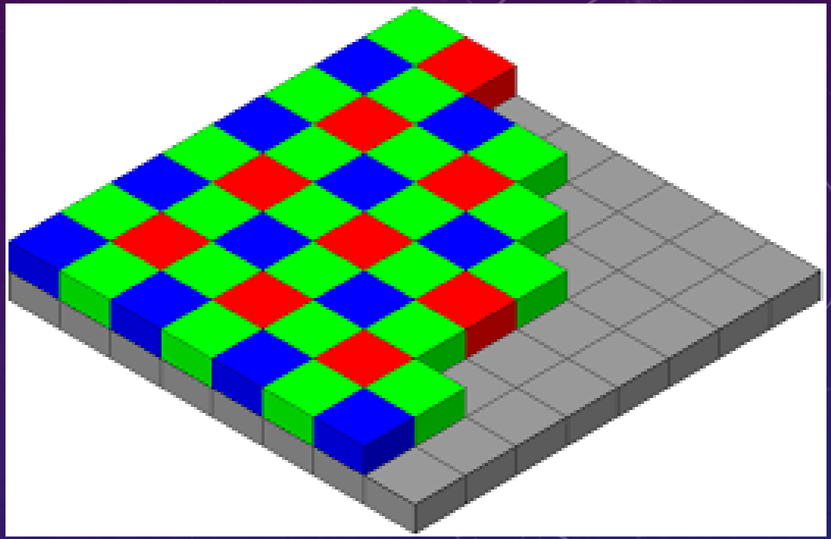
# EQUIPMENT SELECTION
## (OPTICAL TRAIN)

- Optimally sample scope
  - f/10 – 2 micron pixels or smaller (ASI678)
  - f/7 – 1.5 micron pixels or smaller (QHY 5LIII 715C)

    or
  - 3.76 micron pixels – Barlow to f/18 or higher
  - BUT – apparent brightness decreases with f/ ratio
- Atmospheric dispersion corrector
  - Atmosphere bends light differentially depending on wavelength
  - Significant below ~55 degrees elevation
  - Typically require at least f/10 beam
  - RGB Align in AutoStakkert!3 works, but not quite as well
- UV/IR cut filter



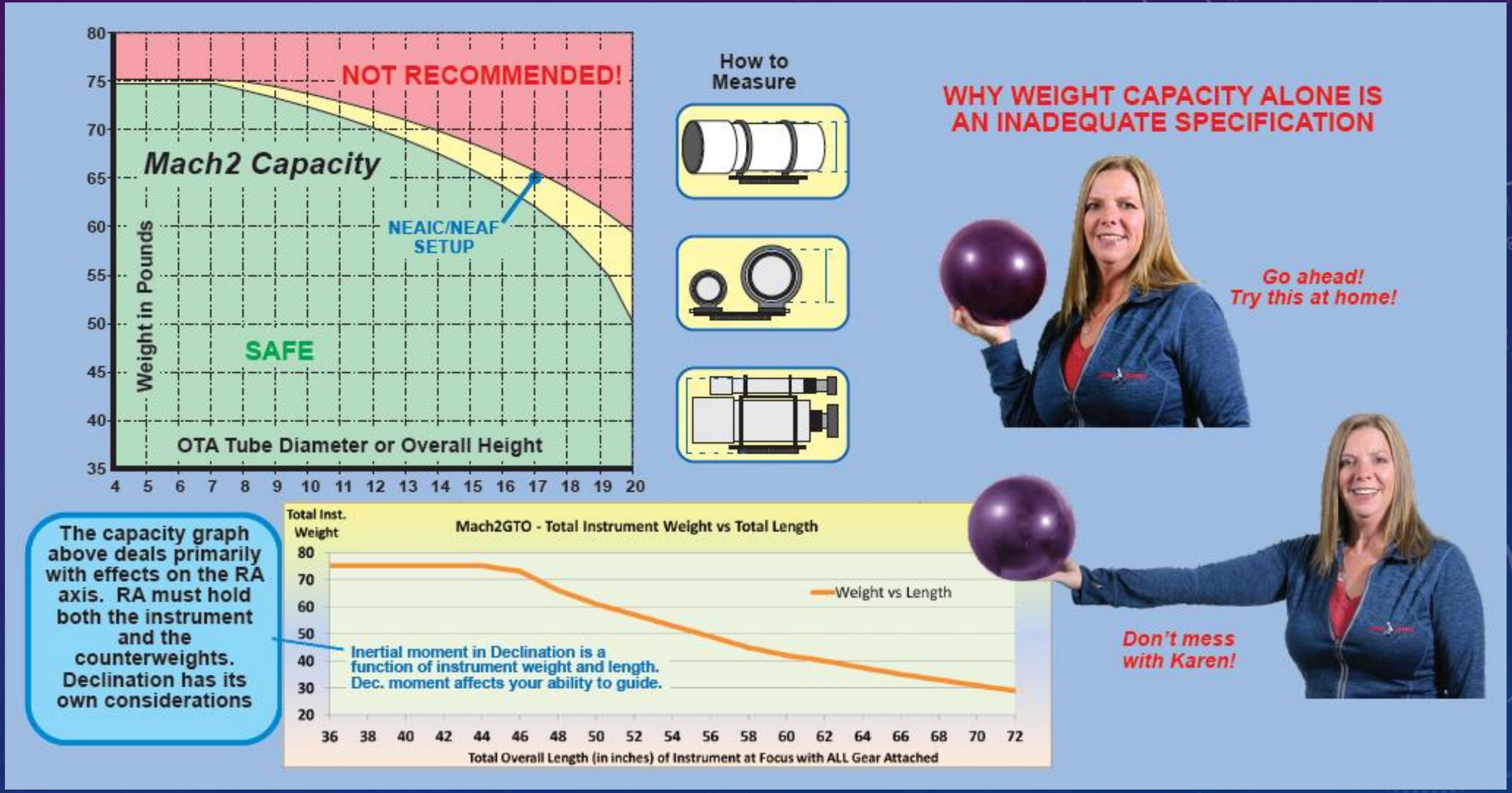

# EQUIPMENT SELECTION
## (CAMERA)



- One shot Color (OSC)
  - Pros: Convenient acquisition, identical seeing conditions in various channels
  - Cons: Gives up some theoretical resolution due to Bayer matrix (can recover to a degree via Bayer Drizzle stacking), lower color contrast
- Monochrome
  - Pros: Higher true resolution and color contrast
  - Cons: more complex imaging train, time consuming acquisition, seeing variability
- High frame rate
  - +/- global shutter
- Don’t need a big sensor
  - Jupiter ~ 1 pixel / mm aperture at optimal sampling
  - Well-aligned finder scope or flip mirror

# EQUIPMENT SELECTION
## (MOUNT / TRIPOD)

- The more rigid / solid, the better
  - Total equipment weight is not the sole consideration
- Minimum tripod leg extension
- Tripod leg spreader
- Tripod weight bags
  - especially for carbon fiber tripods



# EQUIPMENT SELECTION
## (COMPUTER)

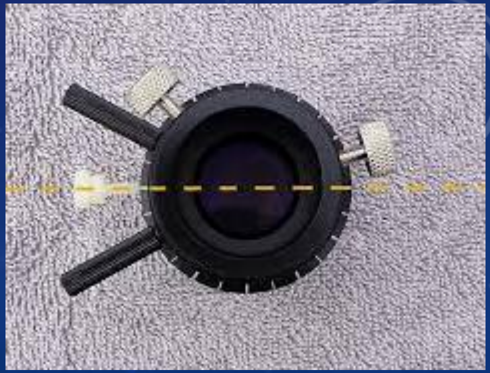
- Prioritize high frame rate / high disk throughput
  - Disable energy saving Power Plans, CPU max state limits, etc.
  - Low power NUCs may not be the best choice
  - Shortest USB3 cables possible
  - Fast storage
    - Internal NVMe SSD - 3 GB / s
    - SSD – 400 MB / s
    - HDD – 120 MB / s
    - USB 3 – 600 MB / s
    - USB 2 – 60 MB / s
- High frame rate VIDEO capture software with native direct camera access
  - ASCOM and DirectShow too slow
  - FireCapture
  - SharpCap

800x800 8-bit video @ 150 fps ≈ 98 MB/s

# IMAGING WORKFLOW

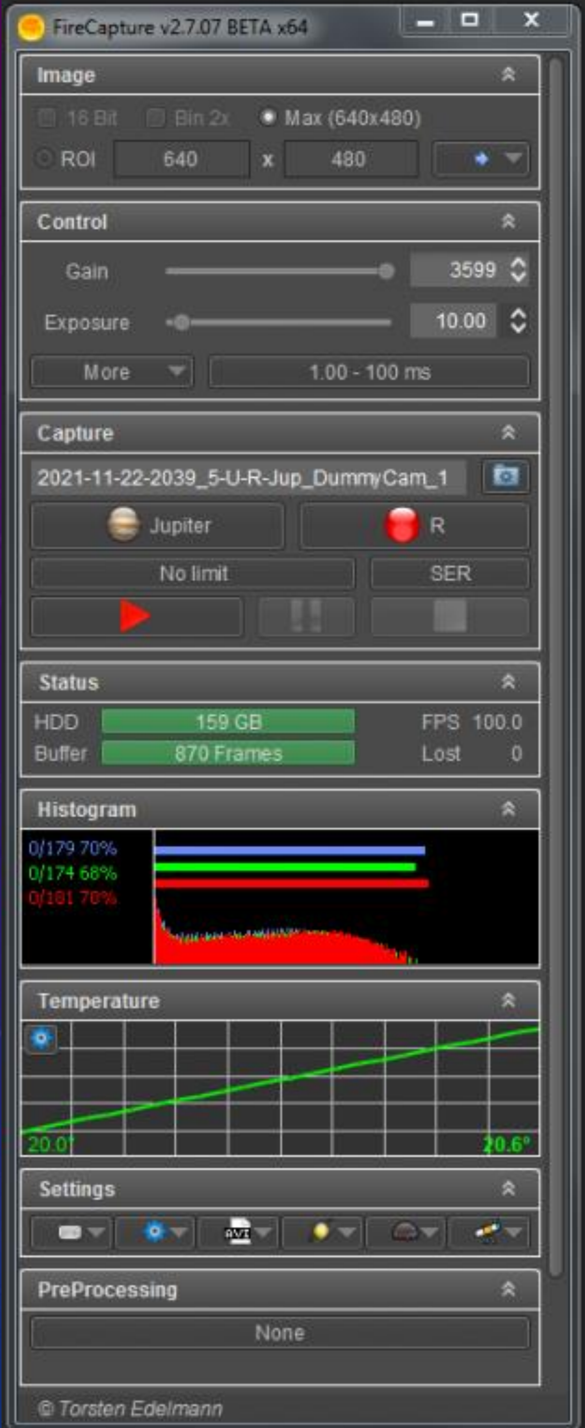
- Select site, tripod / mount setup, polar align, rotate camera to 0˚ orientation
- Start FireCapture
    - Connect mount and focuser
- Slew to and center planet, focus
    - Finder scope, flip mirror, wide field camera (quick detach may be helpful)
    - Gamma may be helpful for focusing, can use FireCapture PreProcessing to enable for preview ONLY
- Select correct FireCapture target profile
    - Jupiter: exposure ~4ms, gain as appropriate for ~90% histogram, full field of view, 240 sec limit
    - USB traffic 100, 8 or 12 bit depending on hardware, RAW (mono) capture, gamma OFF
    - AutoAlign on, reticle on, (optional) deBayer preview on, WinJUPOS compatible naming
- Rotate ADC level to horizon
- ROI to planet
- Set ADC with ADC Assist on
- (Optional) calibrate guiding
- (Optional) image loop script, esp if mono + filters
- Begin capture!

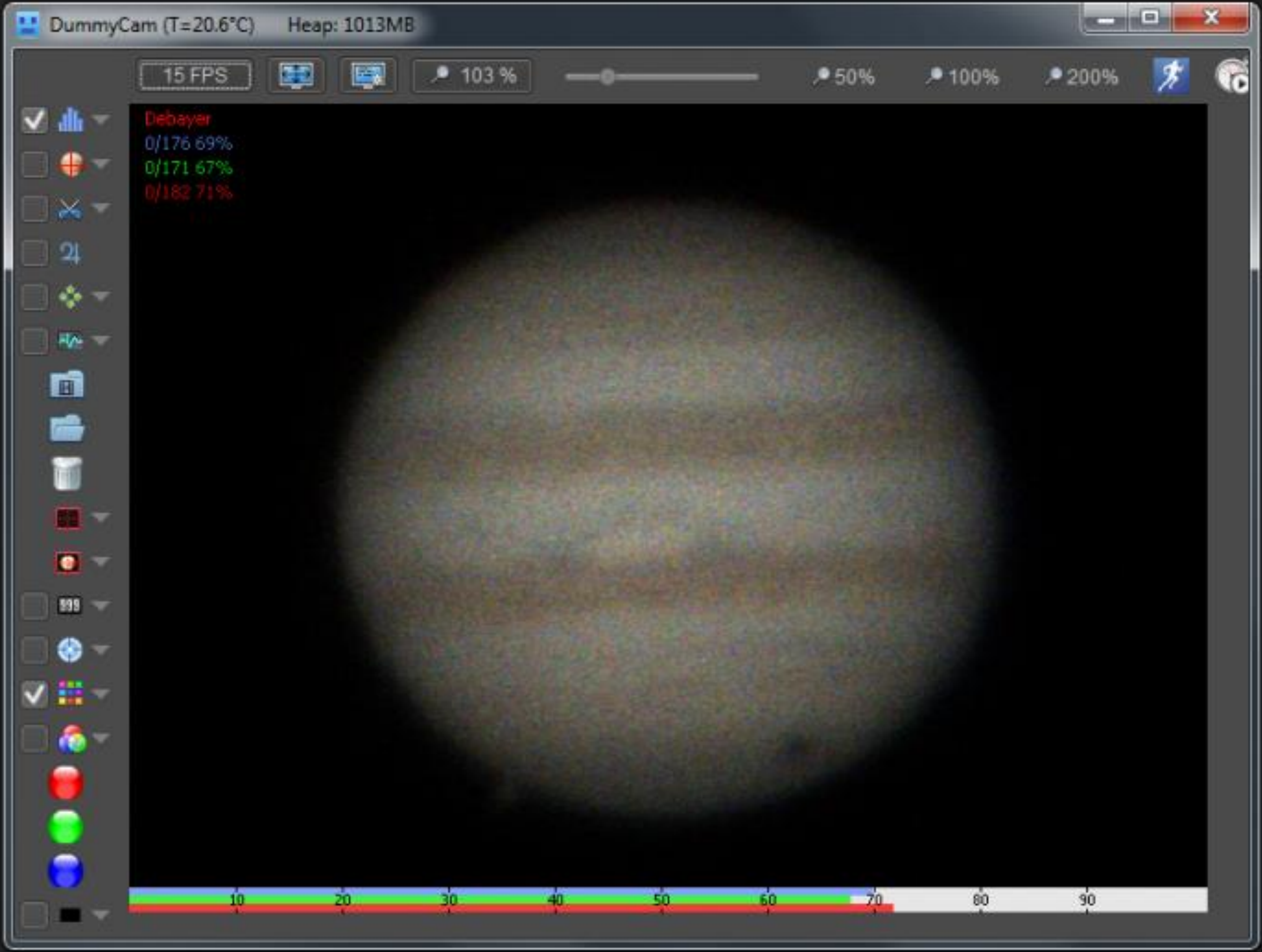




# IMAGING SOFTWARE

- FireCapture
- SharpCap




Comprehensive guide at:
https://skyinspector.co.uk/firecapture-features-explainer/

# PROCESSING

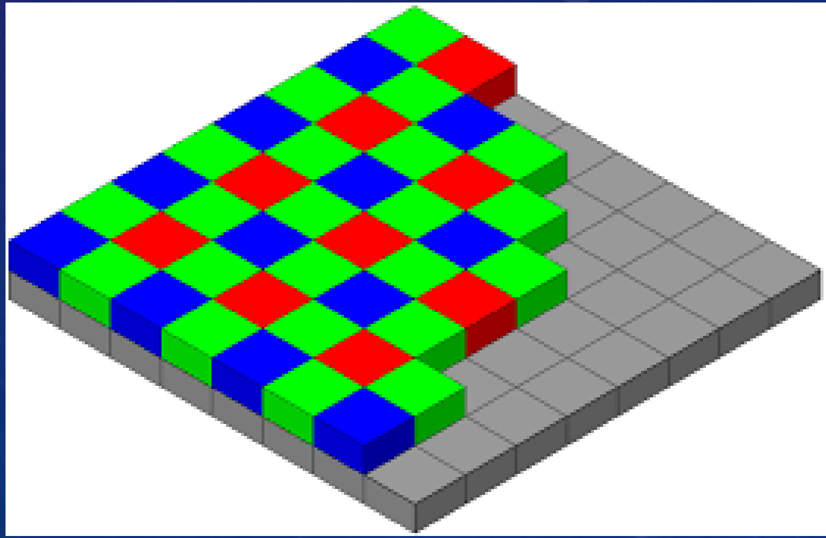
- Stacking
  - AutoStakkert! 3
- Sharpening
  - AstraImage, imPPG
  - WaveSharp
- Color correction and aesthetic tweaks
  - Photoshop, Affinity Photo, other traditional image processing suites

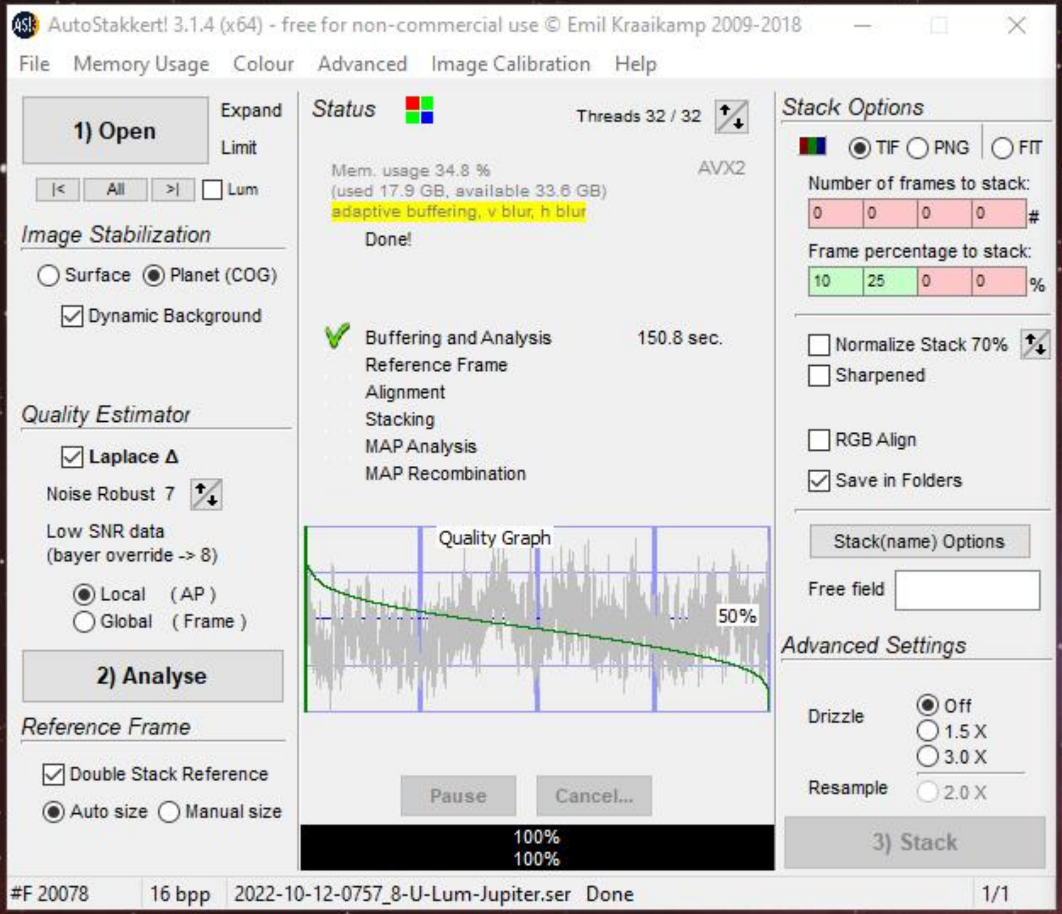
# STACKING

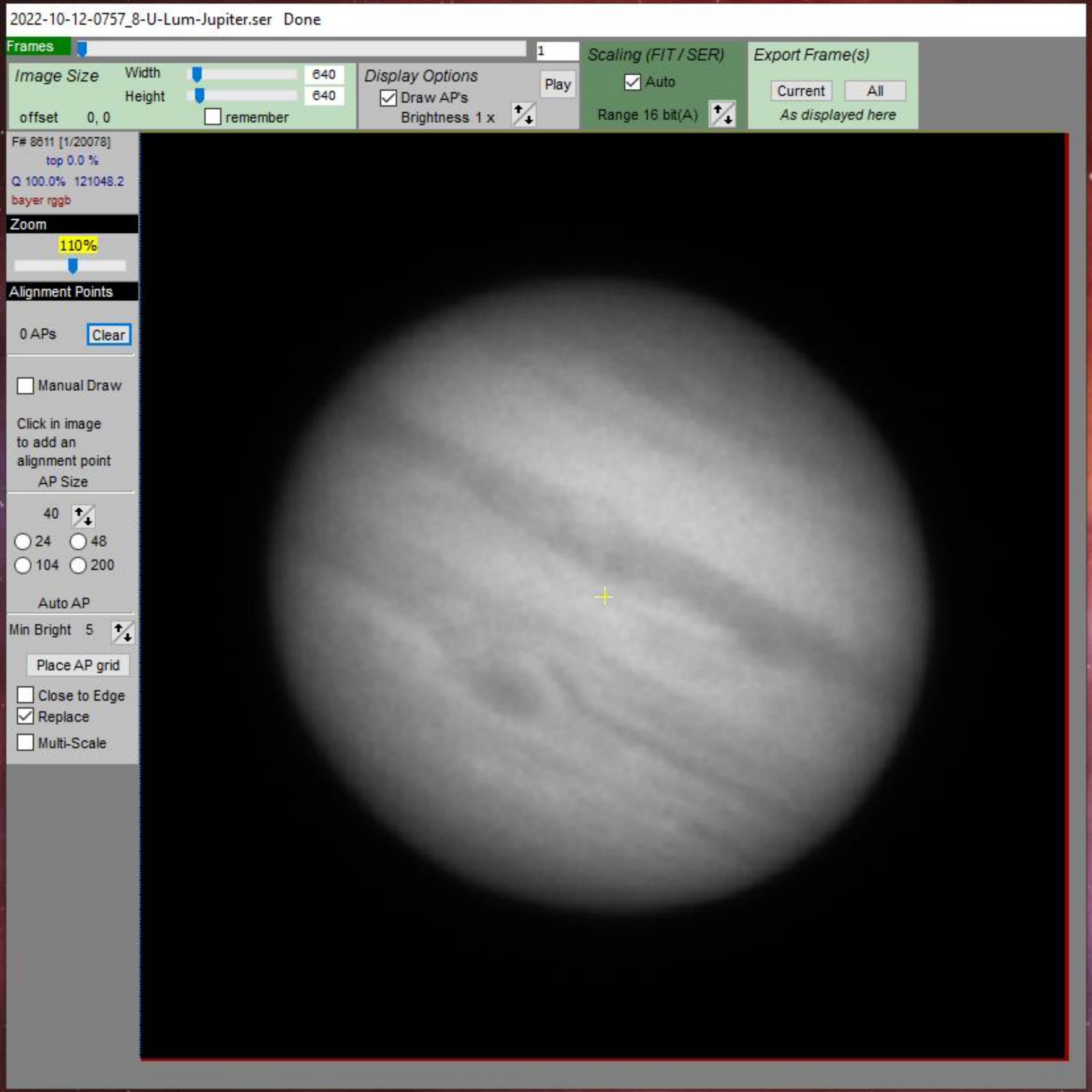
- Increases signal-to-noise ratio
- Increases bit-depth resolution
  - Exact increase depends on number of frames stacked and system noise
- Averages seeing effects into (hopefully) Gaussian point spread function
  - Sets us up for deconvolution
- Bayer drizzle for color reconstruction without interpolation

- But planets are rotating! Jupiter and Saturn have very short rotations, max 4 minute video sequence before motion noticeable in AS!3 stack
  - 3 minutes if stacking entire frame as opposed to alignment points

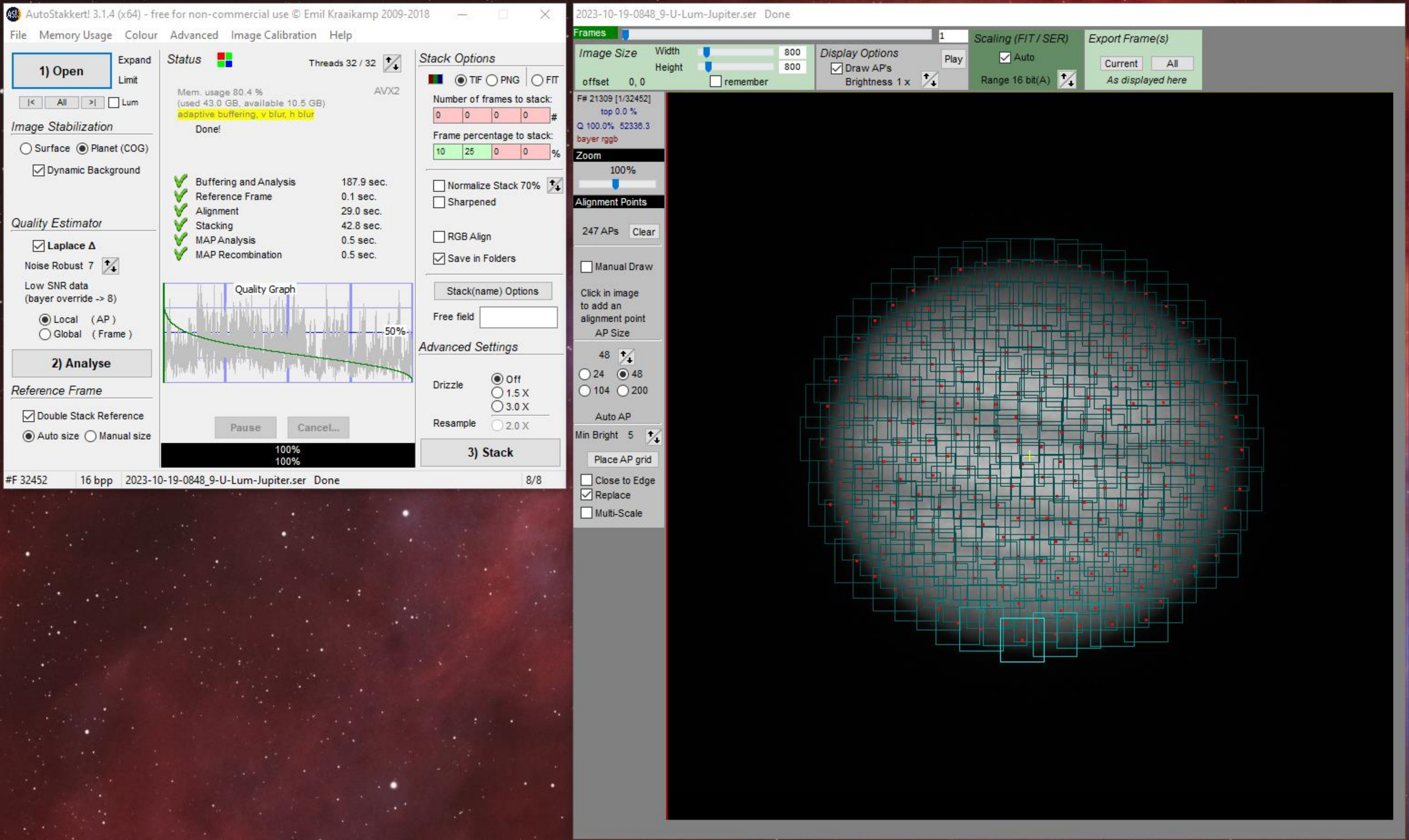
- AutoStakkert! 3






- Open Image
  - select "Planet"
- Analyse
- Place Alignment Points
- Set # or % of frames to stack
- Stack!

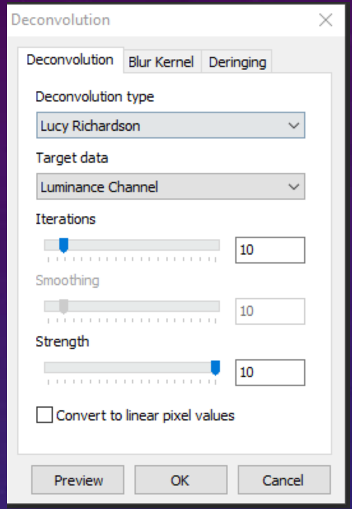

AutoStakkert! 3.1.4 (x64) - free for non-commercial use © Emil Kraaikamp 2009-2018
File Memory Usage Colour Advanced Image Calibration Help
1) Open
Expand
Limit
Status
Threads 32 / 32
Mem. usage 80.4 %
(used 43.0 GB, available 10.5 GB)
adaptive buffering, v blur, h blur
AVX2
Done!
Image Stabilization
Surface Planet (COG)
Dynamic Background
Buffering and Analysis 187.9 sec.
Reference Frame 0.1 sec.
Alignment 29.0 sec.
Stacking 42.8 sec.
MAP Analysis 0.5 sec.
MAP Recombination 0.5 sec.
Quality Estimator
Laplace Δ
Noise Robust 7
Low SNR data (bayer override -> 8)
Local (AP)
Global (Frame)
Quality Graph
50%
2) Analyse
Reference Frame
Double Stack Reference
Auto size Manual size
Pause
Cancel...
100%
100%
Stack Options
TIF PNG FIT
Number of frames to stack:
Frame percentage to stack:
10 25 0 0
Normalize Stack 70%
Sharpened
RGB Align
Save in Folders
Stack(name) Options
Free field
Advanced Settings
Drizzle Off 1.5 X 3.0 X
Resample 2.0 X
3) Stack
#F 32452 16 bpp 2023-10-19-0848_9-U-Lum-Jupiter.ser Done 8/8
2023-10-19-0848_9-U-Lum-Jupiter.ser Done
Frames
Image Size
Width 800
Height 800
offset 0, 0
remember
Display Options
Draw AP's
Brightness 1 x
Play
Scaling (FIT / SER)
Auto
Range 16 bit(A)
Export Frame(s)
Current All
As displayed here
F# 21309 [1/32452]
top 0.0 %
Q 100.0% 52336.3
bayer rggb
Zoom
100%
Alignment Points
247 APs Clear
Manual Draw
Click in image to add an alignment point
AP Size
48
24 48
104 200
Auto AP
Min Bright 5
Place AP grid
Close to Edge
Replace
Multi-Scale

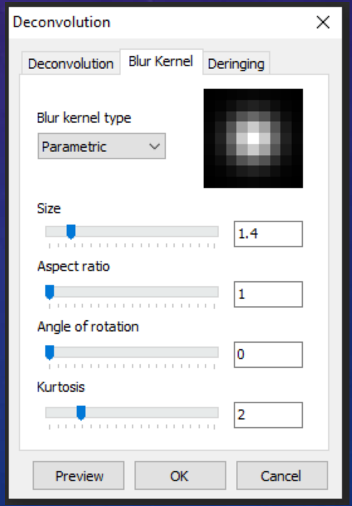
# SHARPENING

- Mathematically "undo" blurring (deconvolution)
  - Must be first step
- (OPTIONAL) Derotate and combine stacked images with WinJUPOS
- Increase feature edge contrast
  - Multi-scale (wavelet) techniques
  - Traditional, e.g. Unsharp mask

# DECONVOLUTION

- Mathematically reduces PSF back into a single point
- Lucy-Richardson most commonly used
    - Specify size of PSF and number of iterations, optionally kurtosis and eccentricity
- Trial and error process to identify correct PSF size
    - Batch processing for consistency
- AstraImage
- imPPG

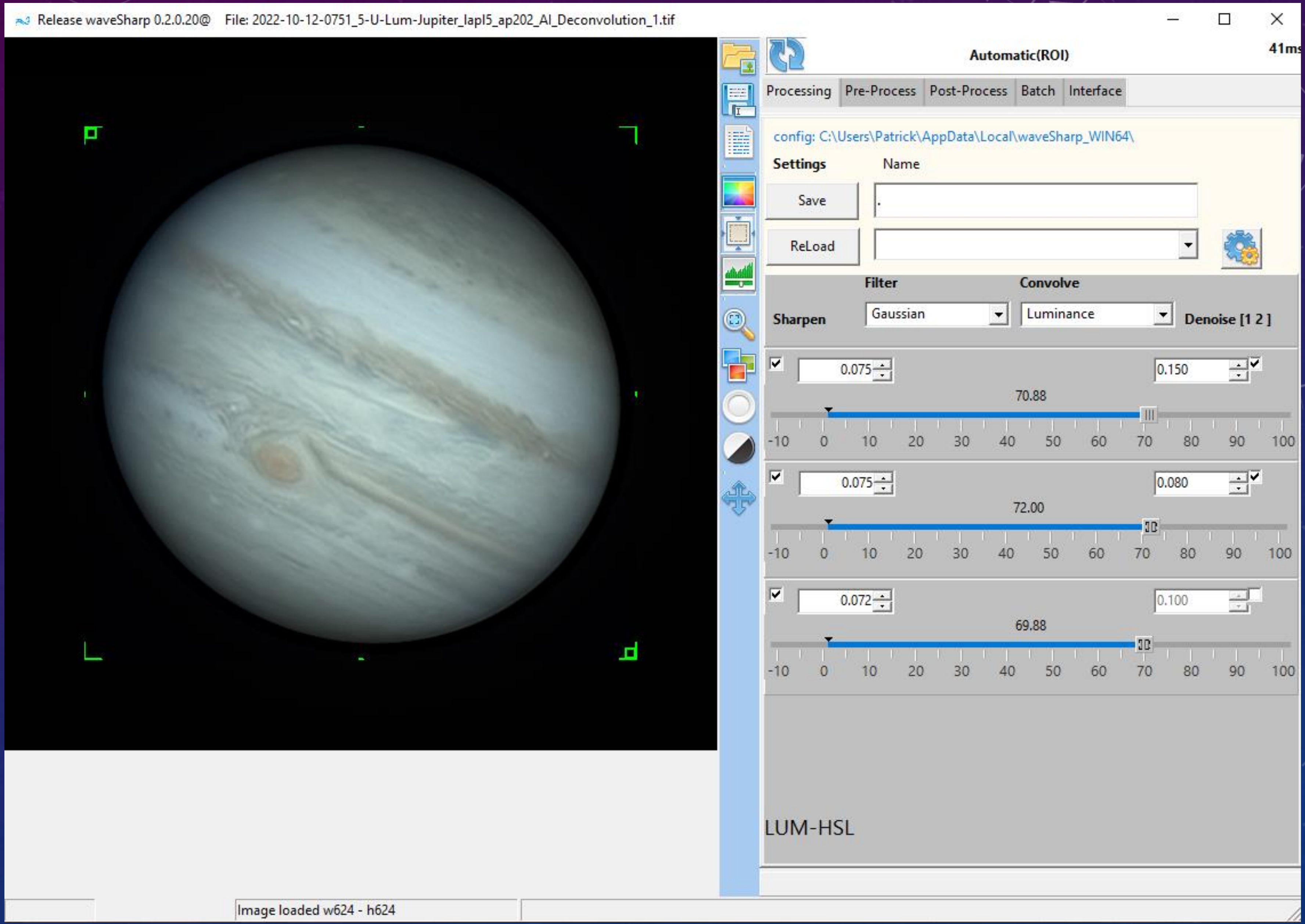



# SHARPENING

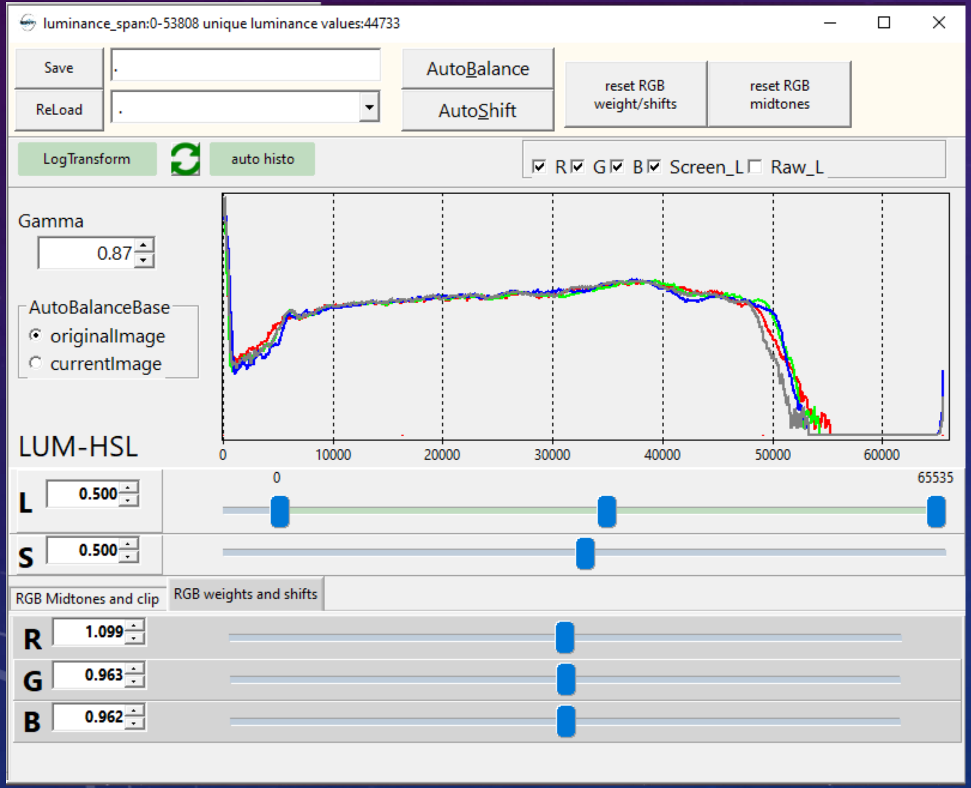
- Numerous techniques
- Multiscale sharpening can “trap” noise at small scale

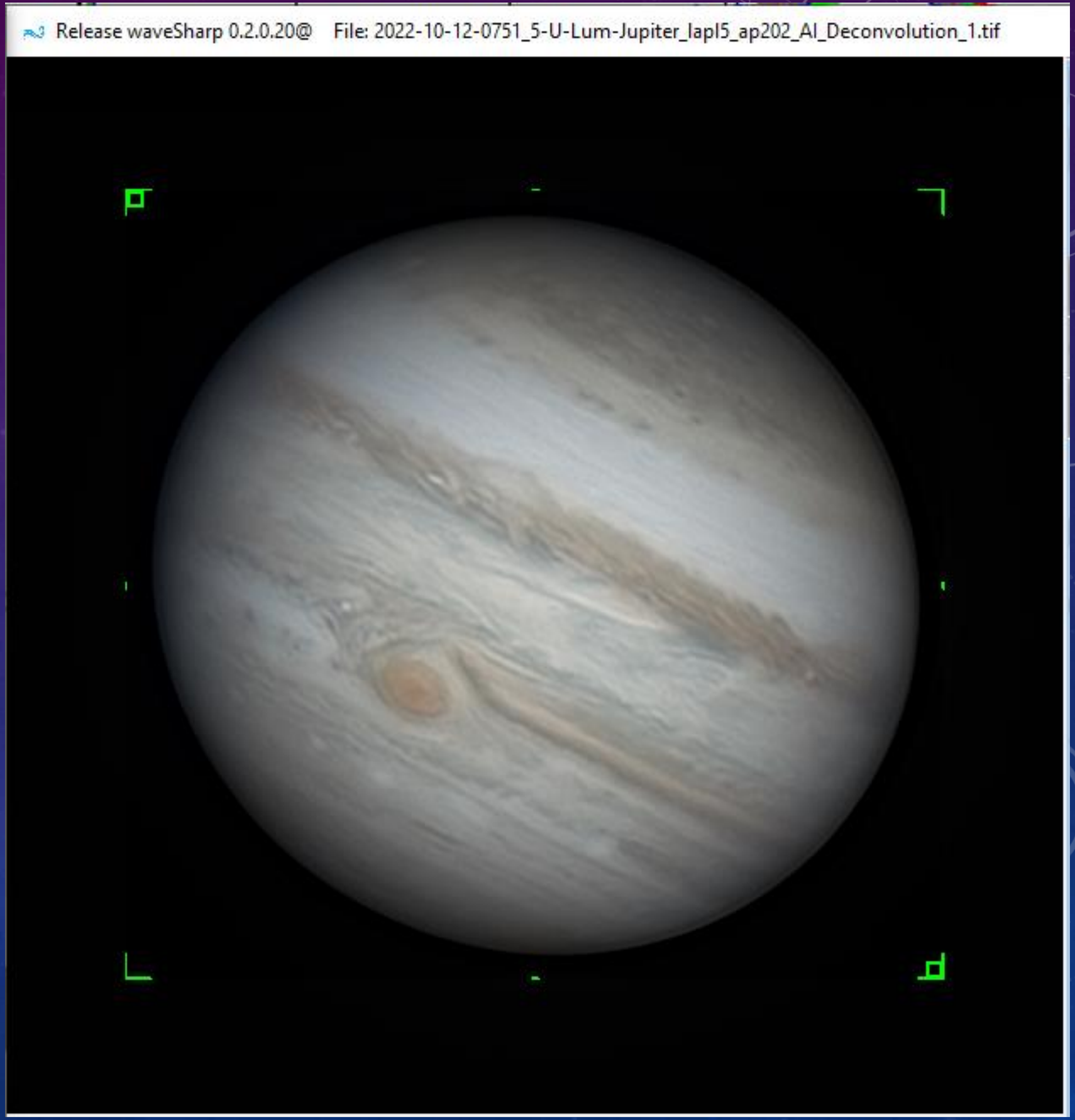
- WaveSharp nee Registax 6
- AstraImage



# COLOR CORRECTION

- WaveSharp has AutoBalance function



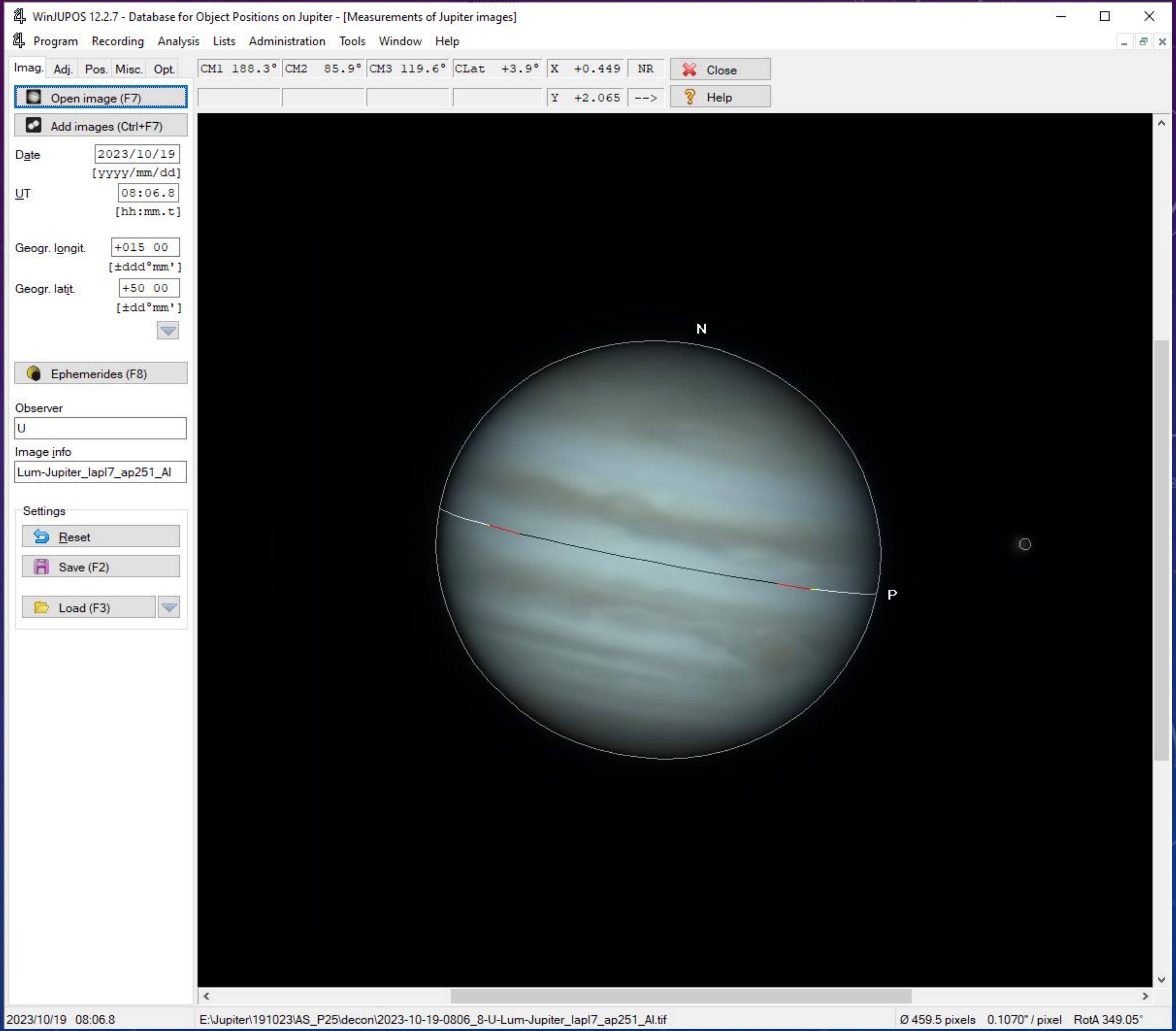
# WINJUPOS

- Can “derotate” images to allow for stacking of stacks
- Allows integration time longer than 4 minutes
- FireCapture simplifies data input by encoding UTC time in filename
- AutoDetect works best on sharpened images, but may cause artifacts

- Measure individual stacked images
- De-rotate and combine

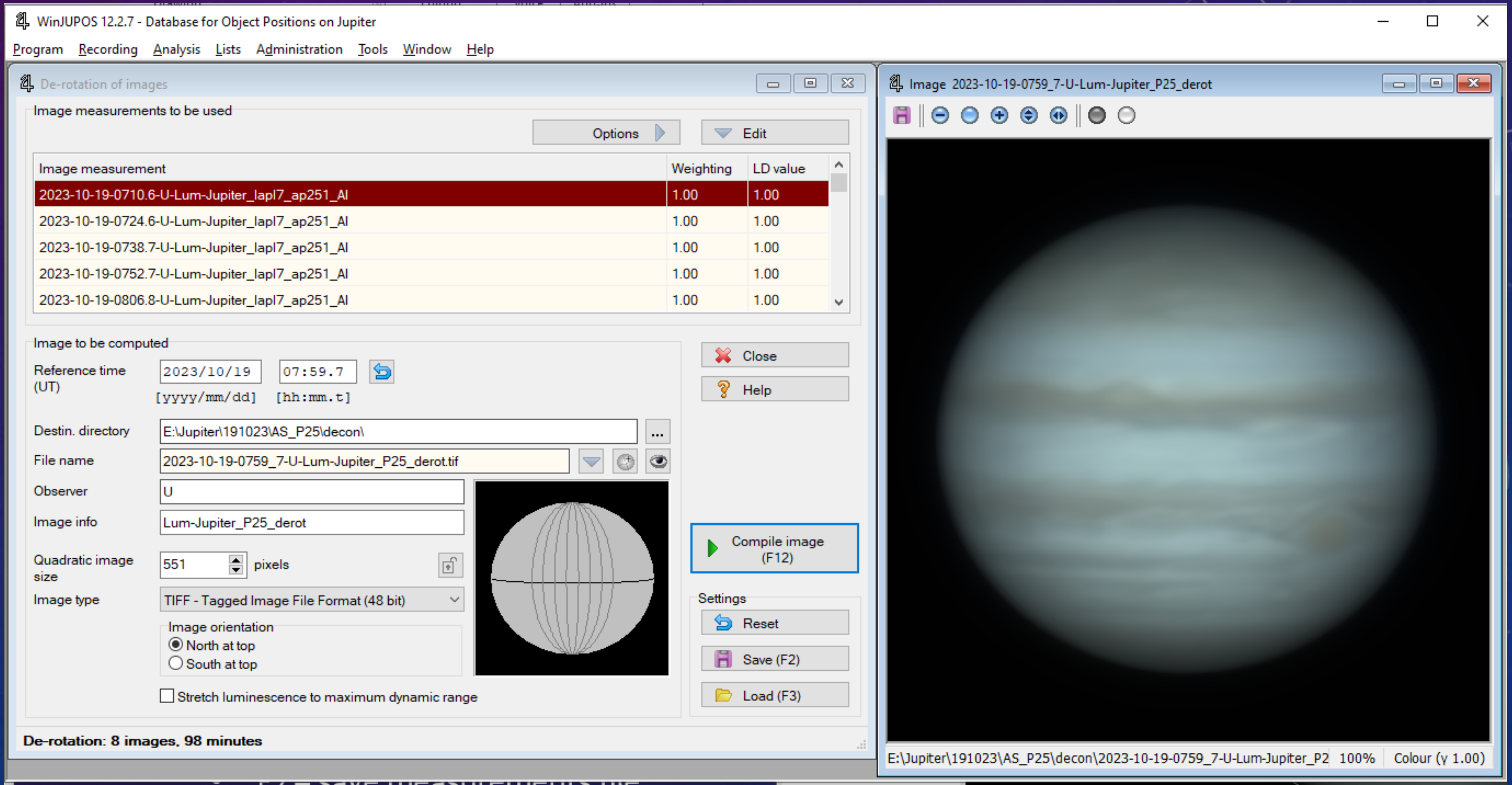
# WINJUPOS

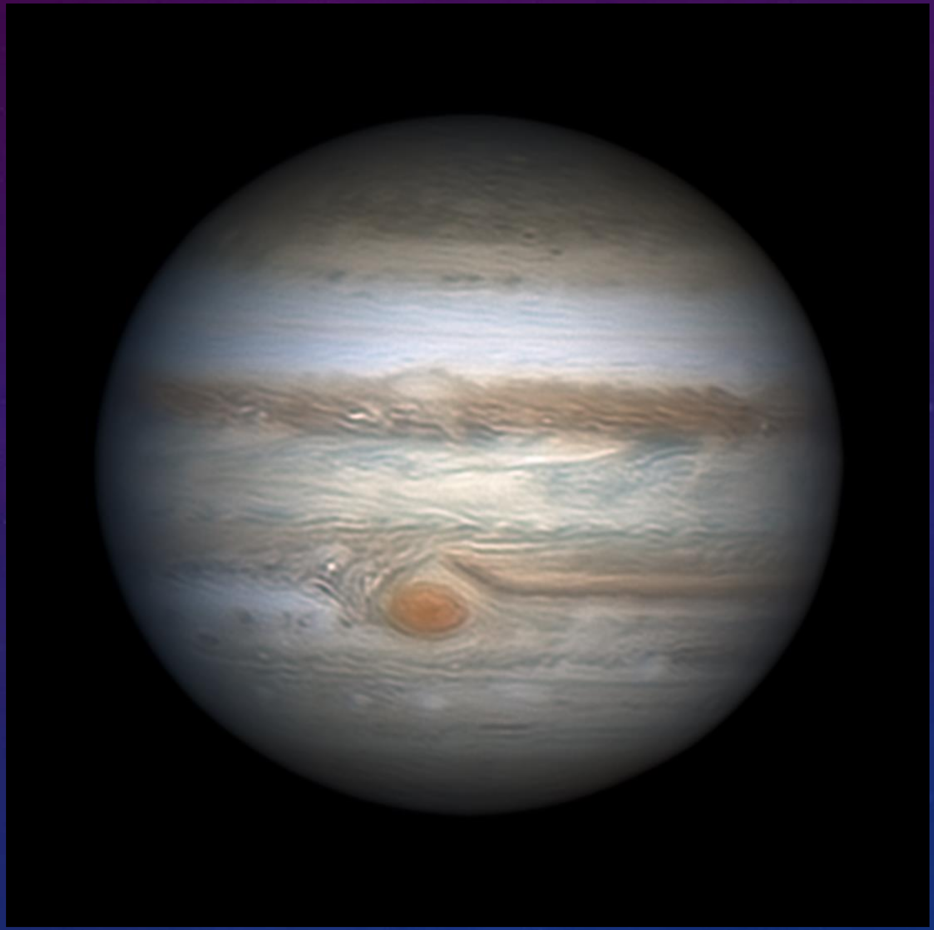
- Measure individual stacked, sharpened images
- Recording / Image Measurement…
  - F7 - load image
  - F11 – autodetect
  - F2 – save measurements file



# WINJUPOS

- Tools / De-rotation of images…
  - Add measurement files
  - Compile Image





# SUMMARY

- High resolution planetary imaging is hard
- You can’t ever beat Mother Nature (the seeing)
- Every little thing is important
- Size matters

- Largest feasible aperture
- Barlow and camera pixel size selection to achieve optimal sampling based on f/ratio
- Atmospheric and thermal management
- High frame rate video capture
- Deconvolution / sharpening

- FireCapture, AutoStakkert! 3, AstraImage, WaveSharp, +/- WinJUPOS