Autoguiding on the Macintosh

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Macintosh Astronomy Workshop I
Illinois Institute of Technology

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Bob Piatek

Presenter's Background

- President - Fishcamp Engineering, a design engineering services firm.
- Education - BSEE, Rochester Institute of Technology
- Passion - Amateur Astronomy and digital imaging.

Autoguiding - key to success in deep sky imaging

M27 - 10 x 240 second exposures

- Very faint objects require long time exposures
- Single frame exposures from 30 seconds to greater than 10 minutes
- Requires very good tracking of the telescope to eliminate star trails

Progressively longer exposure = longer star trails

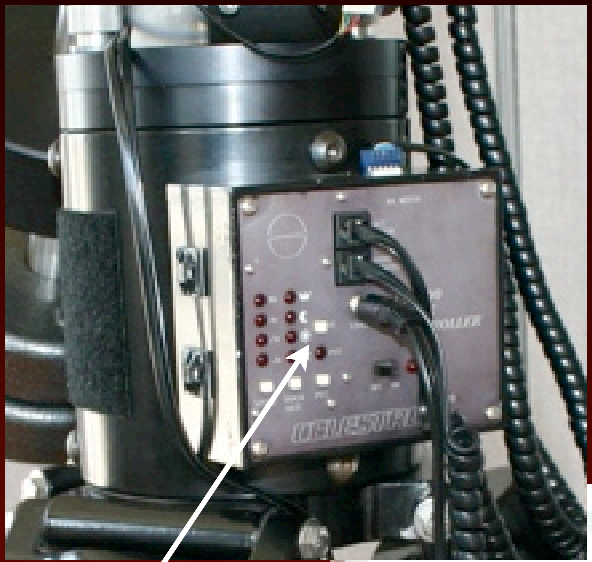
M82

Another Example

M13

Ways to minimize star tracking errors

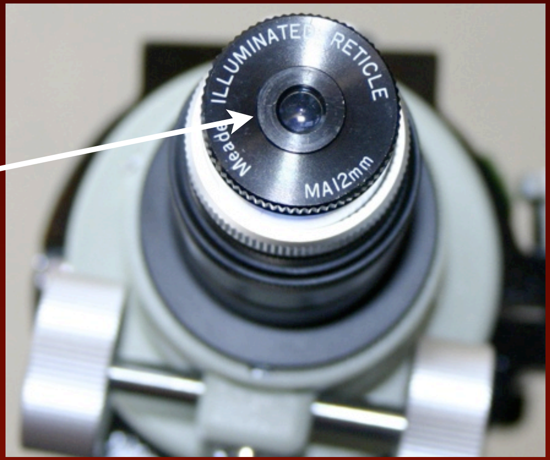
- Use an equatorial mount
- Good polar alignment
- PEC - periodic error correction
- Manual Guiding



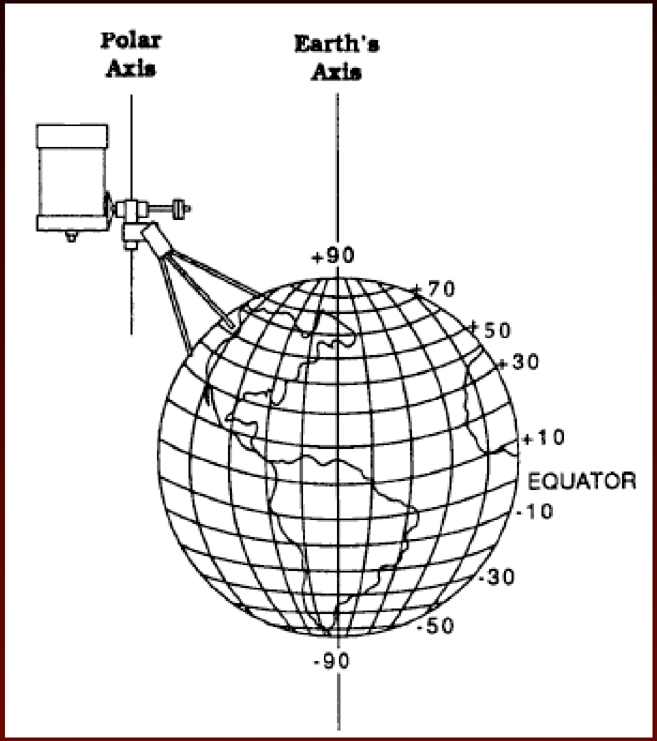
PEC Control

Polar Alignment Scope

Illuminated Reticle



Equatorial Mounts



- Popular German Equatorial design
- 2-axis movement
- Polar axis parallel to earth's own axis
- Polar axis driven by clock drive to compensate for earth's rotation
- Popular fork mounted GOTO SCT telescopes can track the stars but will give field rotation if not wedge mounted.

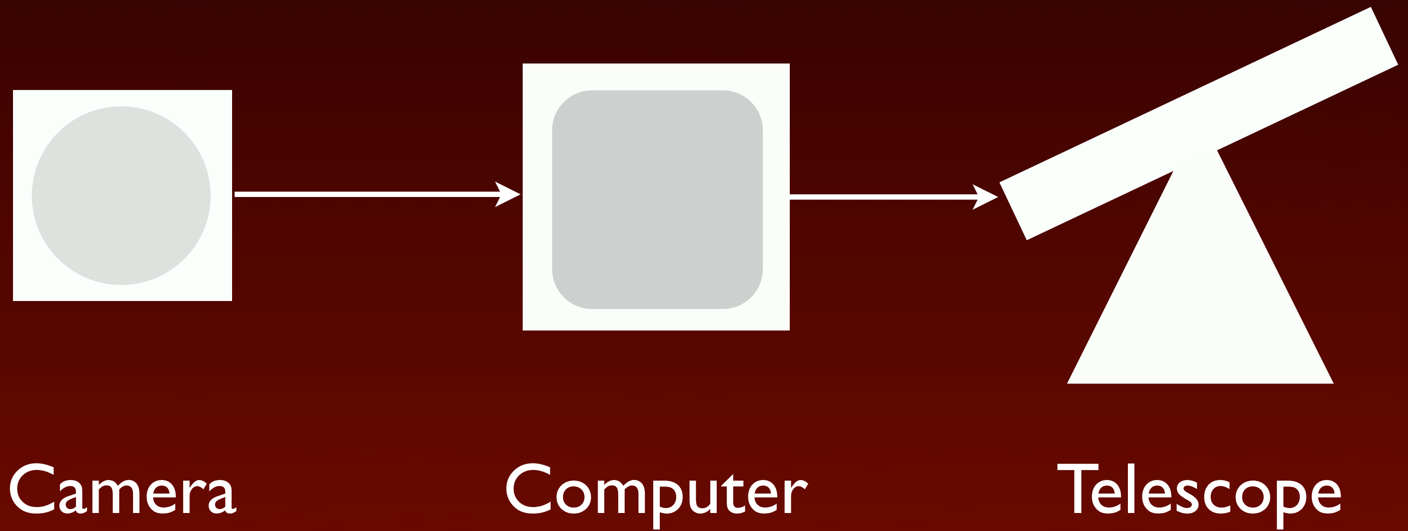
Problems still exist

- Random errors caused by lack of smoothness in drive gears or bearings or contamination by dirt and dust.
- Mechanical looseness or flaws in the mount
- Telescopes with moving mirrors can have image shift over a long time period.
- Tripod and mount flexure as the telescope weight shifts

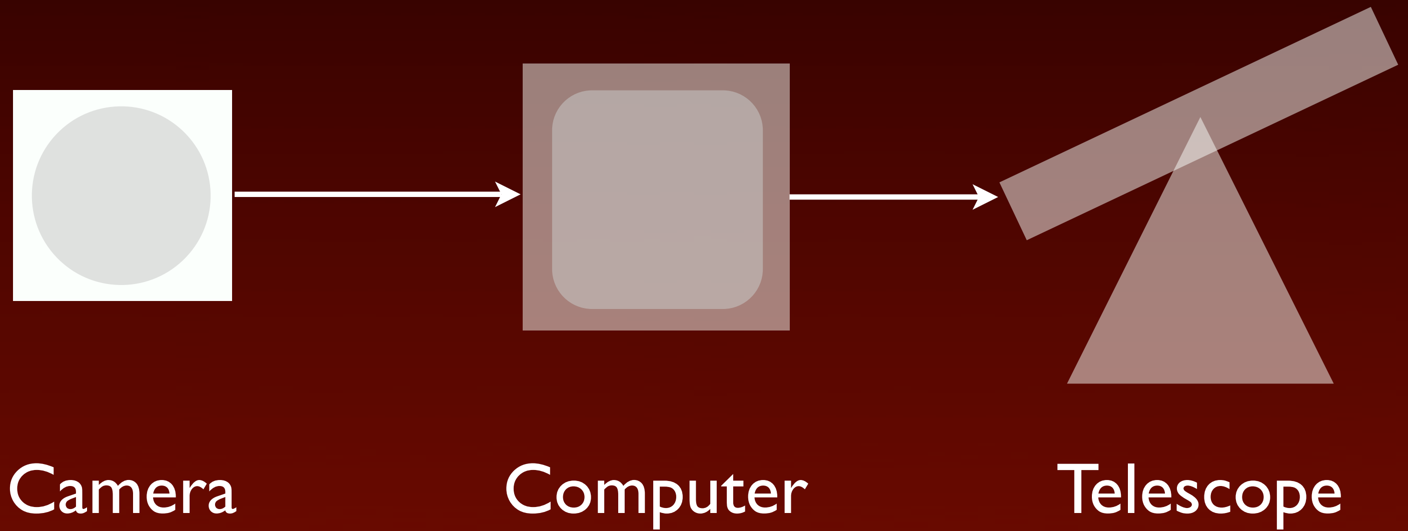
Solution - Autoguiding

- Feedback loop that monitors the position of the mount and makes small corrections.
- Digital camera takes a picture of a ‘guide’ star every few seconds.
- If the position of the star changes, then a correction command is sent to the telescope’s mount controller
- The process repeats for the length of the exposure.
- Corrections are made far more accurately and timely than manual guiding can achieve.

Autoguider Components



Autoguider Components



Camera

- Many different camera types suitable
  - WEB Cams
  - Dedicated Astro Cameras
  - Dedicated Guider Cameras
  - Integrating Video Cameras
- Optical path to guide star
  - Separate guide telescope
  - Off-axis guider

WebCams

- USB or FireWire interface
- Drivers available from IOExperts (Quicktime VDIG)

  http://www.ioxperts.com
- Limited to exposures < 133mS

  Will limit how faint of guide star you can use

WebCam Eyepiece Adapter

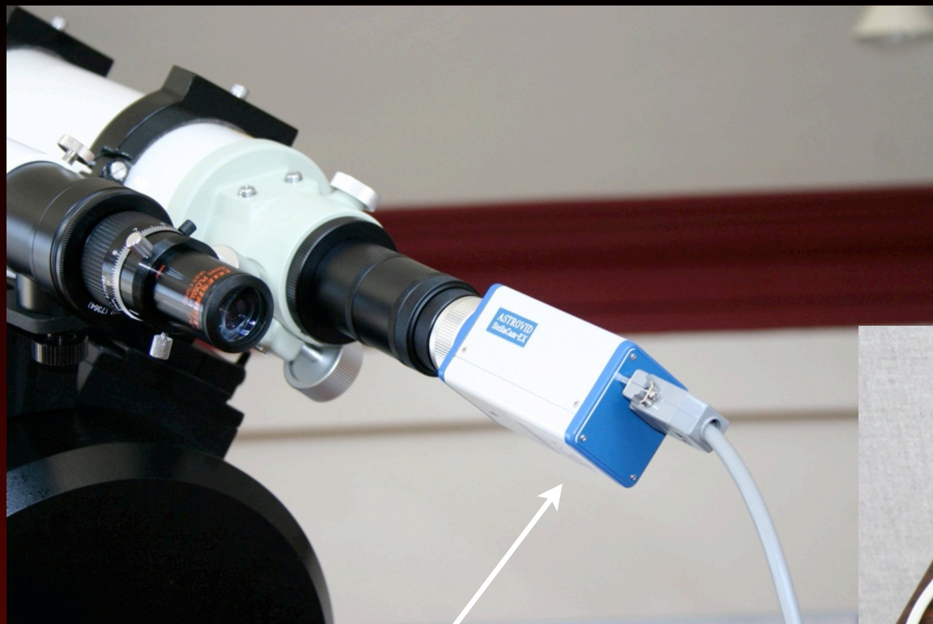
- Replaces stock WebCam lens
- Some allow use of threaded light filters
  - LPR
  - IR
- Open design so dust contamination of sensor is a problem

Dedicated Astro Cameras

- Available from a number of manufacturers
  - Starlight Express
  - SBIG
  - Others
- Usually use USB interface
- Custom software drivers or dedicated application support required
- Best image quality and low-light performance

Integrating Video Cameras

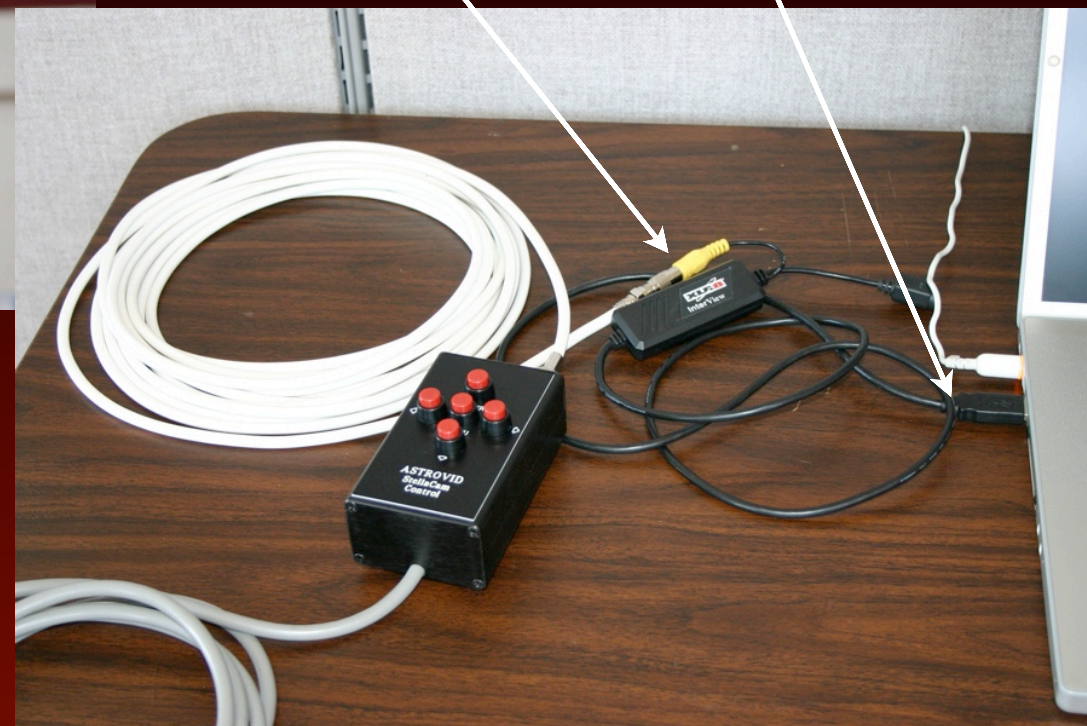
- Modified security cameras
- In-between WebCams and Dedicated Astro cams in sensitivity
- Usually have analog video outputs (requires digitizer)
- Digitizer interface boxes are available in USB and Firewire
  - Canopus, ADS, XLR8



StellacamEX on guidescope

Analog Video

USB interface



StellacamEX - XLR8 Interview

Guide Camera Optical Path

- Separate guidescope
  - more flexible in choosing guide stars
  - subject to flexure between the main scope and guide scope
- Off-axis guider
  - Not subject to flexure problem
  - Limited choice of guidestars
    - position

Separate guide scope

- Different focal length from main scope
  - wider field of view gives more guide star choices
  - can use barlow or powermate lenses to change focal length
- Smaller aperture scope has less light gathering power

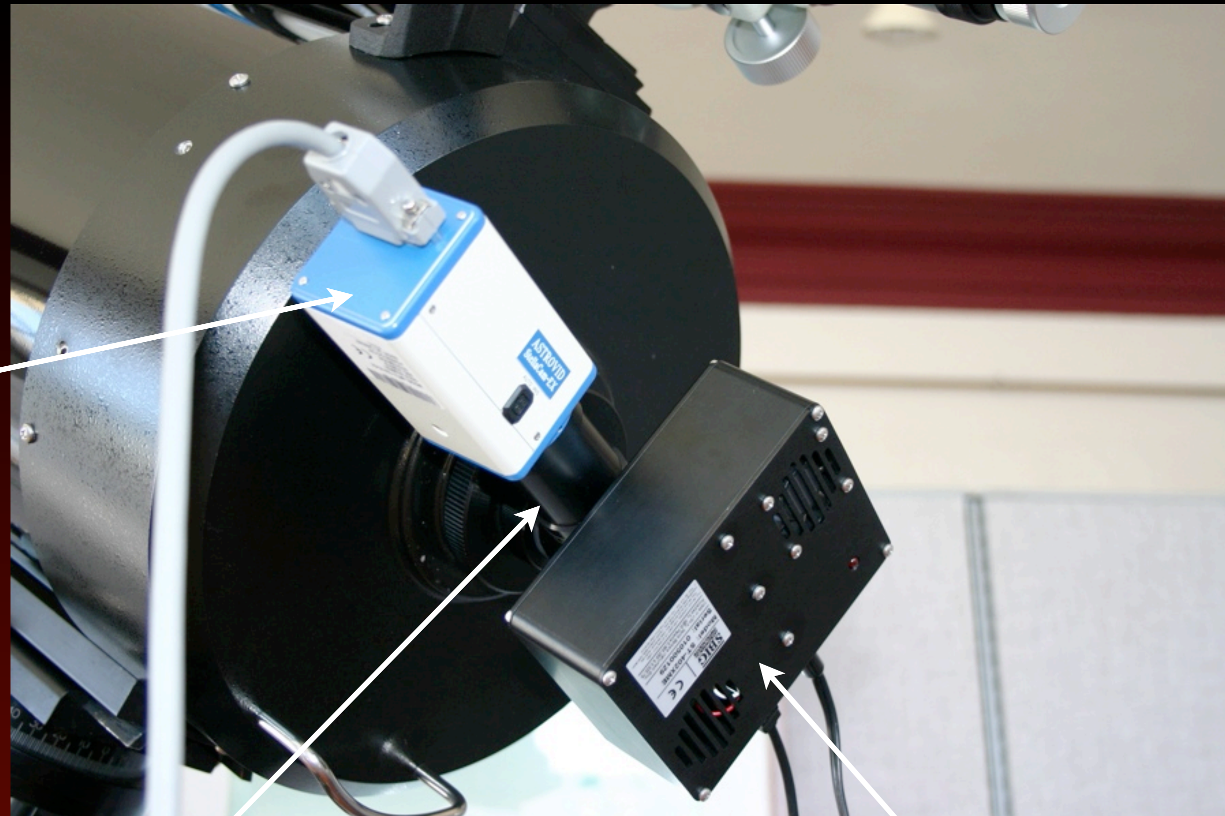
prism

Guide camera port

Off-axis guider

- Uses the same scope for guiding and imaging
- small prism on edge of field of view for pick up
    - need to rotate to find a good guide star
    - guide star near periphery of field

Guide Camera

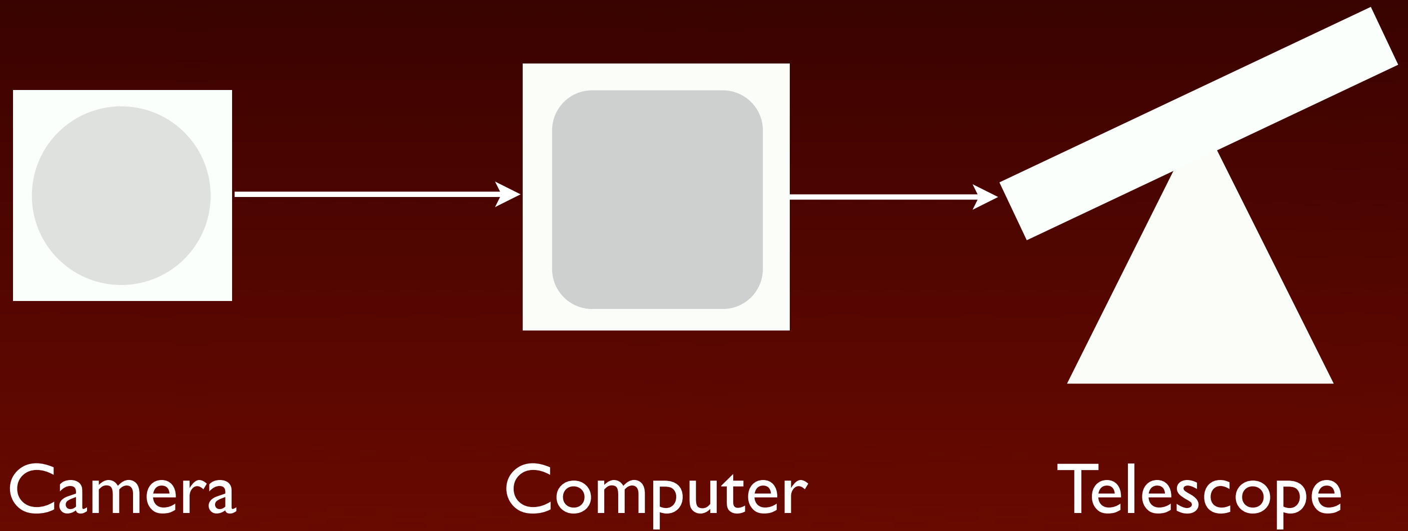


Off-axis pick off

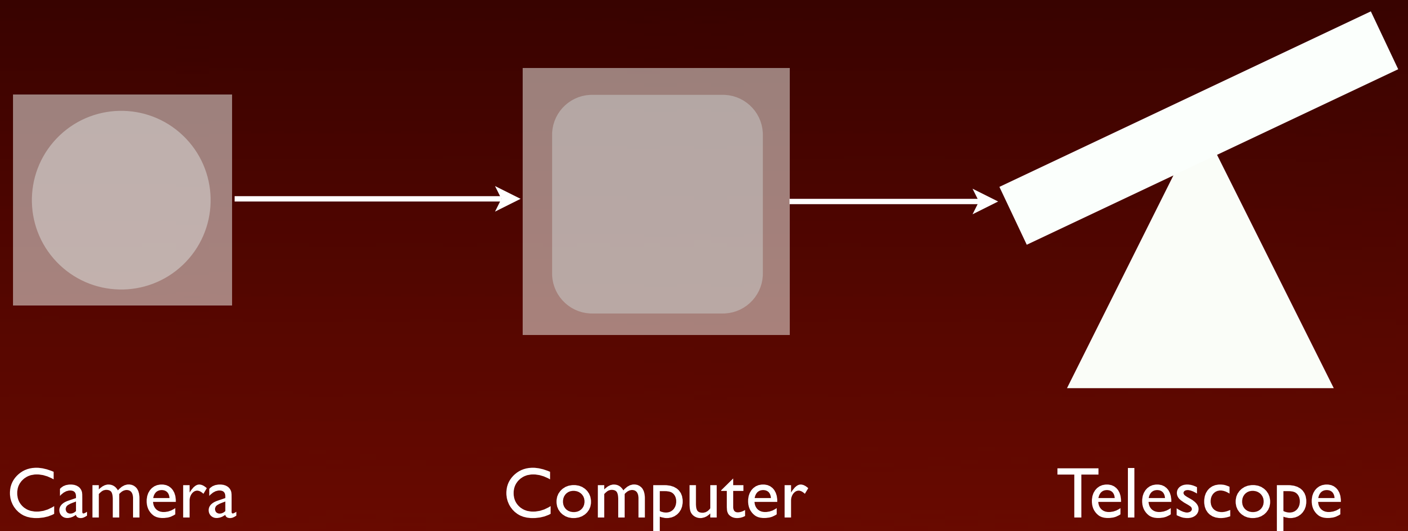
Imaging Camera

Off-axis Setup

Autoguider Components



Autoguider Components



Telescope Interface

- Mount must have interface capability
  - computer or autoguider interface port
  - motor drive
- 2 main types of interfaces:
  - Serial RS-232
    - requires USB - RS-232 converter for computer
  - ST4 style relay interface
    - requires relay box interface
      - dedicated
      - on camera

Dedicated Relay Interface Box

USB Interface
to computer

ST4 style interface to
telescope mount

Status LEDs
(N, S, W, E)

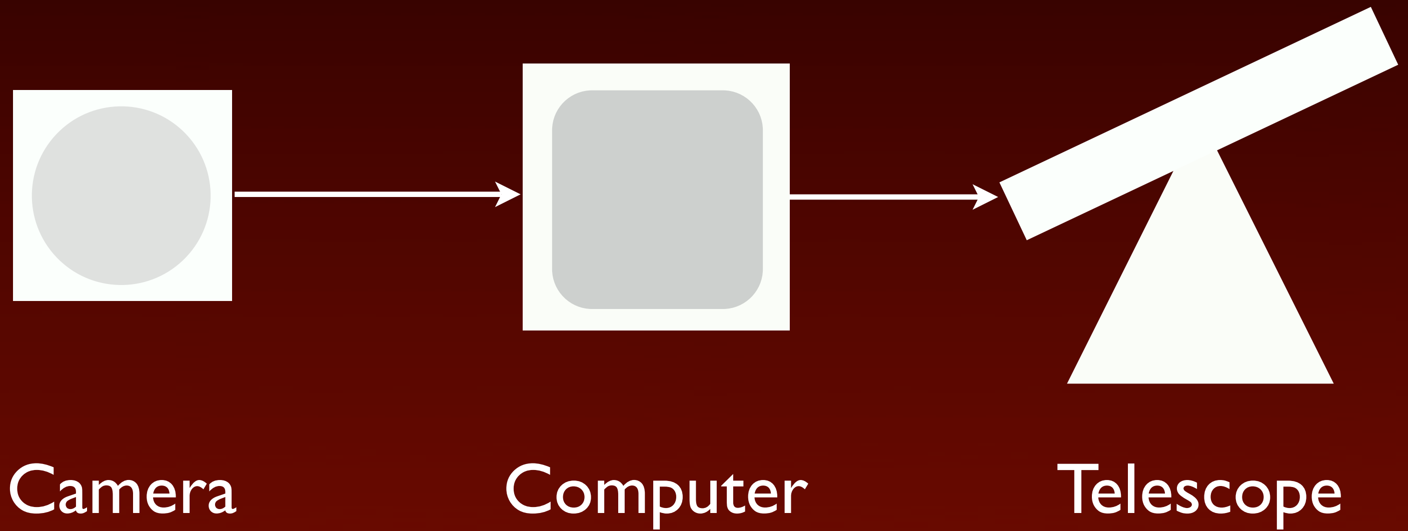
On Camera Interface

USB Interface
to computer

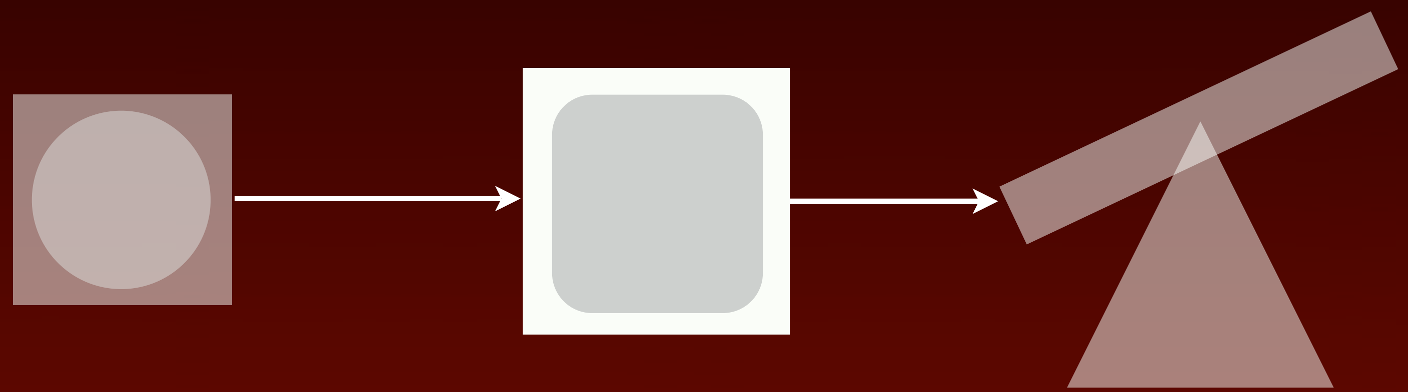
ST4 style interface to
telescope mount

Telescope Interface

Autoguider Components



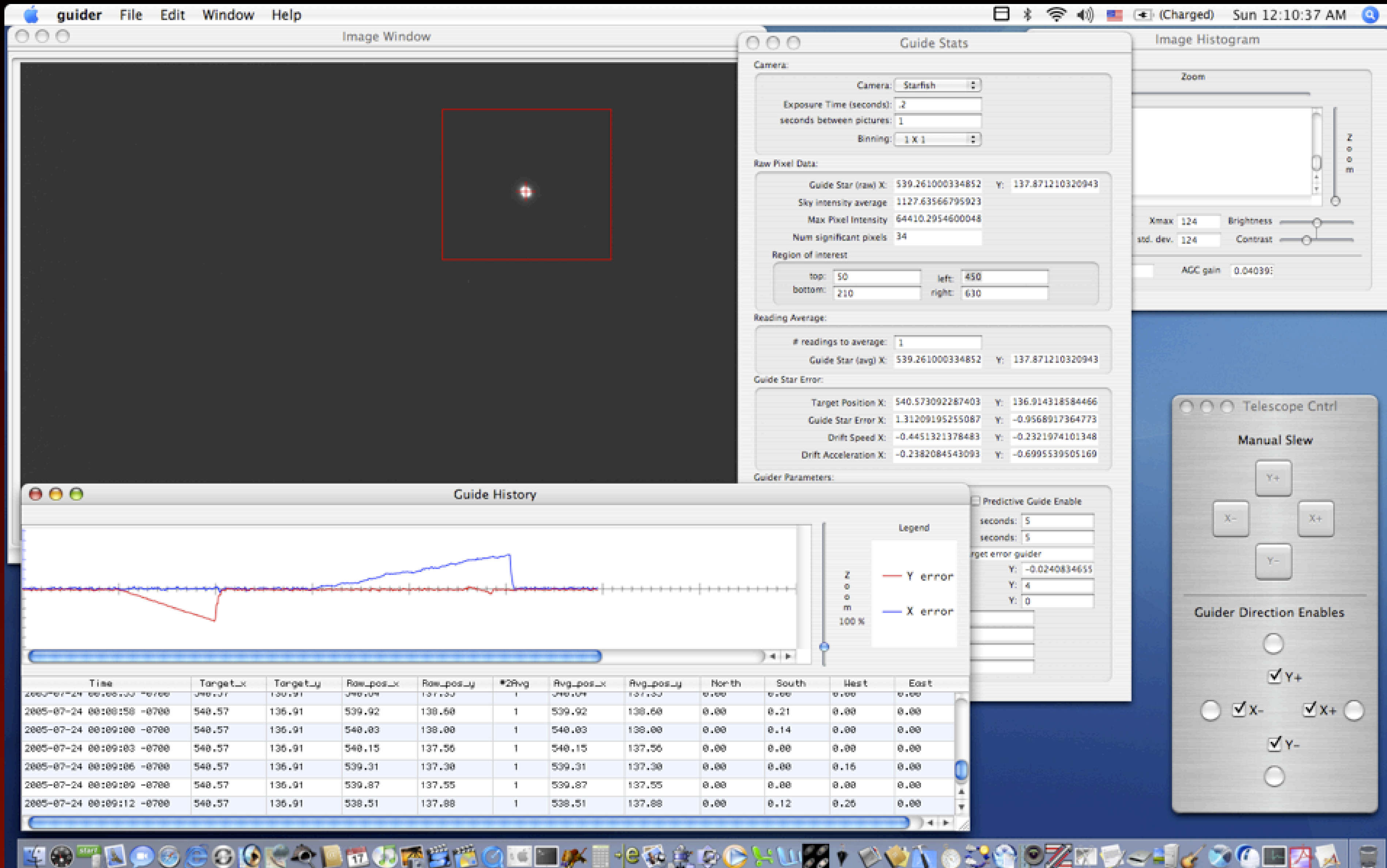
Autoguider Components



Camera Computer Telescope

Computer

- Control program running on the computer provides the 'smarts' in the system.
- Interfaces to guide camera and telescope mount
- Several programs available on the PC platform
  - CCDOPS
  - MaximDL
  - AstroArt
  - GuideDog
- Recent introductions support MacOS X
  - Equinox
  - Astro IIDC
  - Keith's AstroImager
  - fcGuide

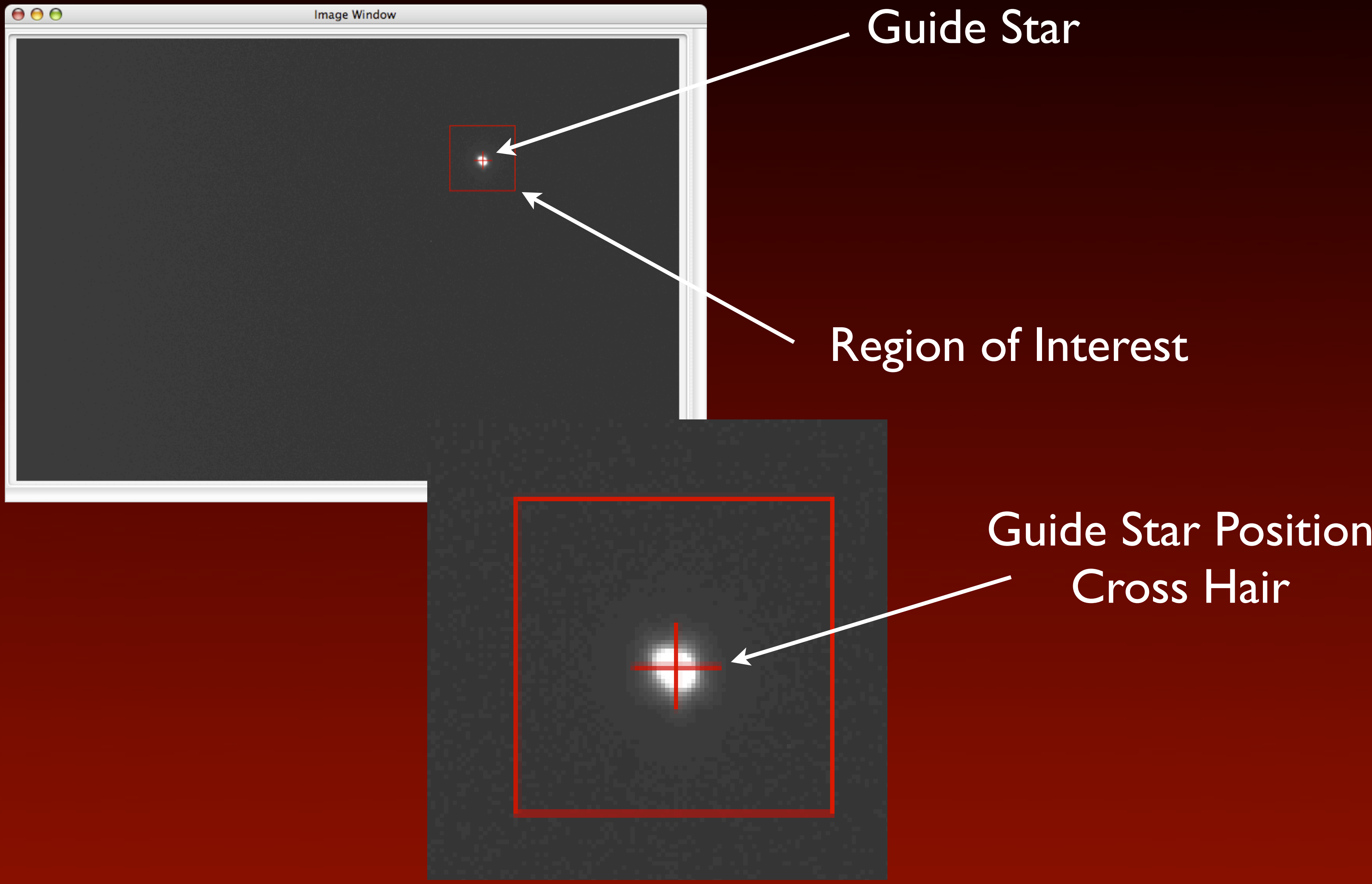


Fishcamp Engineering - fcGuide

History

- Development started in summer 2004
- No solutions available on MacOS X platform at that time
- Built custom USB - Relay interface box
- StellacamEX and XLR8 Interview used for image capture
- Solution a bit cumbersome with multiple boxes and interface cables

Image Capture

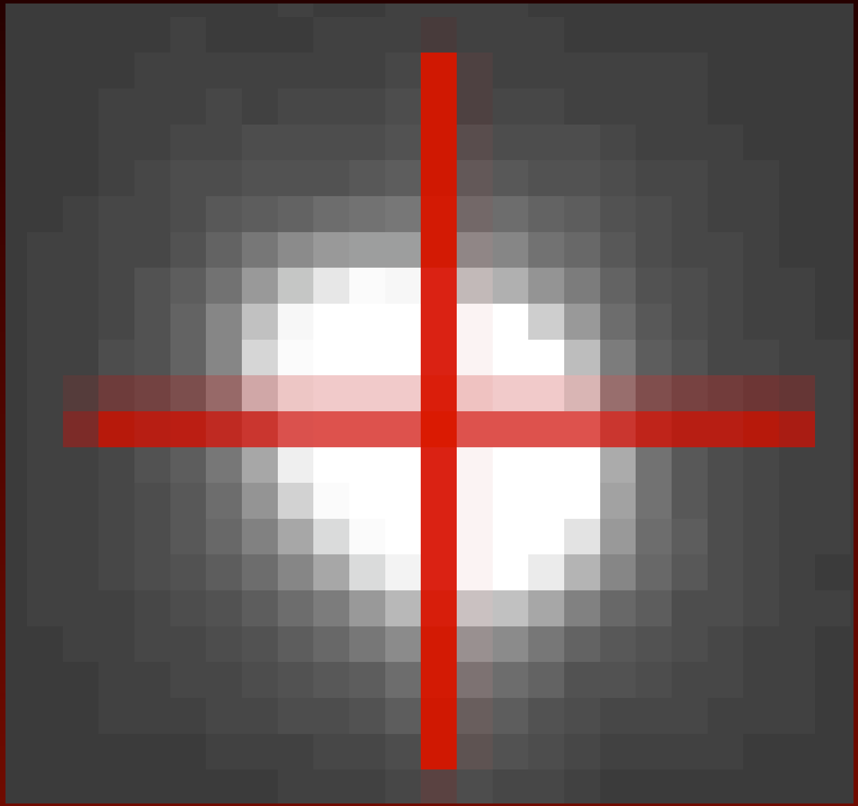


Calculating Guide Star Location

1) Centroid Calculation
   - Fast, easy calculation
   - benefits from 'aperture mask'

2) Cross Correlation
   - highly noise immune
   - very CPU intensive

Centroid Calculation

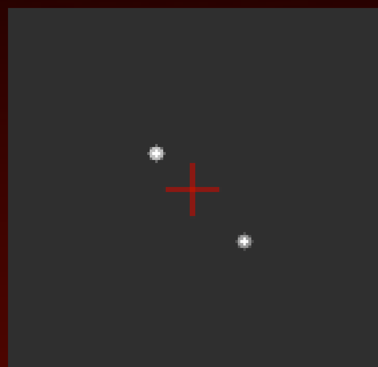


Magnified Star Image

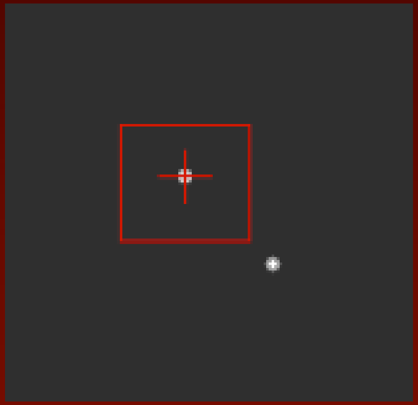
- Star imaged by multiple sensor pixels
- Each pixel's intensity weighted by position of pixel in frame
- 'Center of Gravity' calculation
- Intensity of background 'sky' subtracted
- Intensity threshold
- Region of Interest aperture
- Sub-pixel precision

Centroid Calculation

- 'Center of Gravity' calculation problems:
  - multiple star field
  - Planes / Satellites cause errors
  - noisy image with 'twinklers'
- Region of Interest mask solves most of these problems.



No Aperture Mask



With Aperture Mask

Cross Correlation

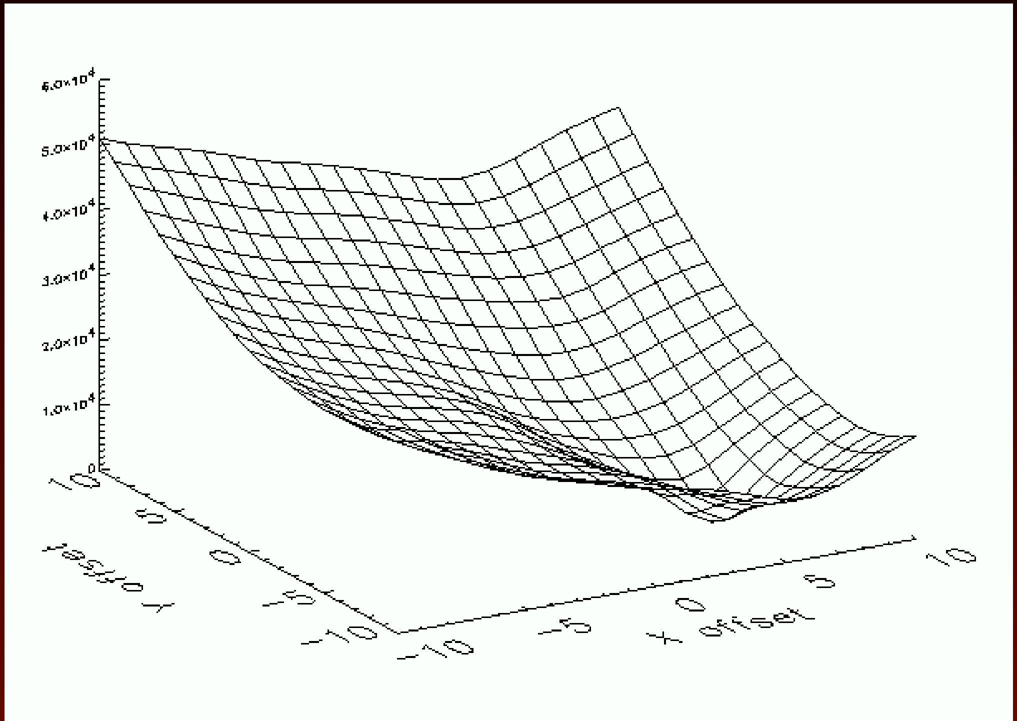
$$p_1 \otimes p_2 = \sum_{w_1,w_2} (p_1 - p_2)^2$$

p1, p2 = pixel index (2d)
w1, w2 = domain of interest

- Robust in high noise environments
- Very CPU intensive because of the total number of pixel operations involved.
- Opportunity for calculation acceleration in dedicated signal processing hardware.

Cross Correlation Example

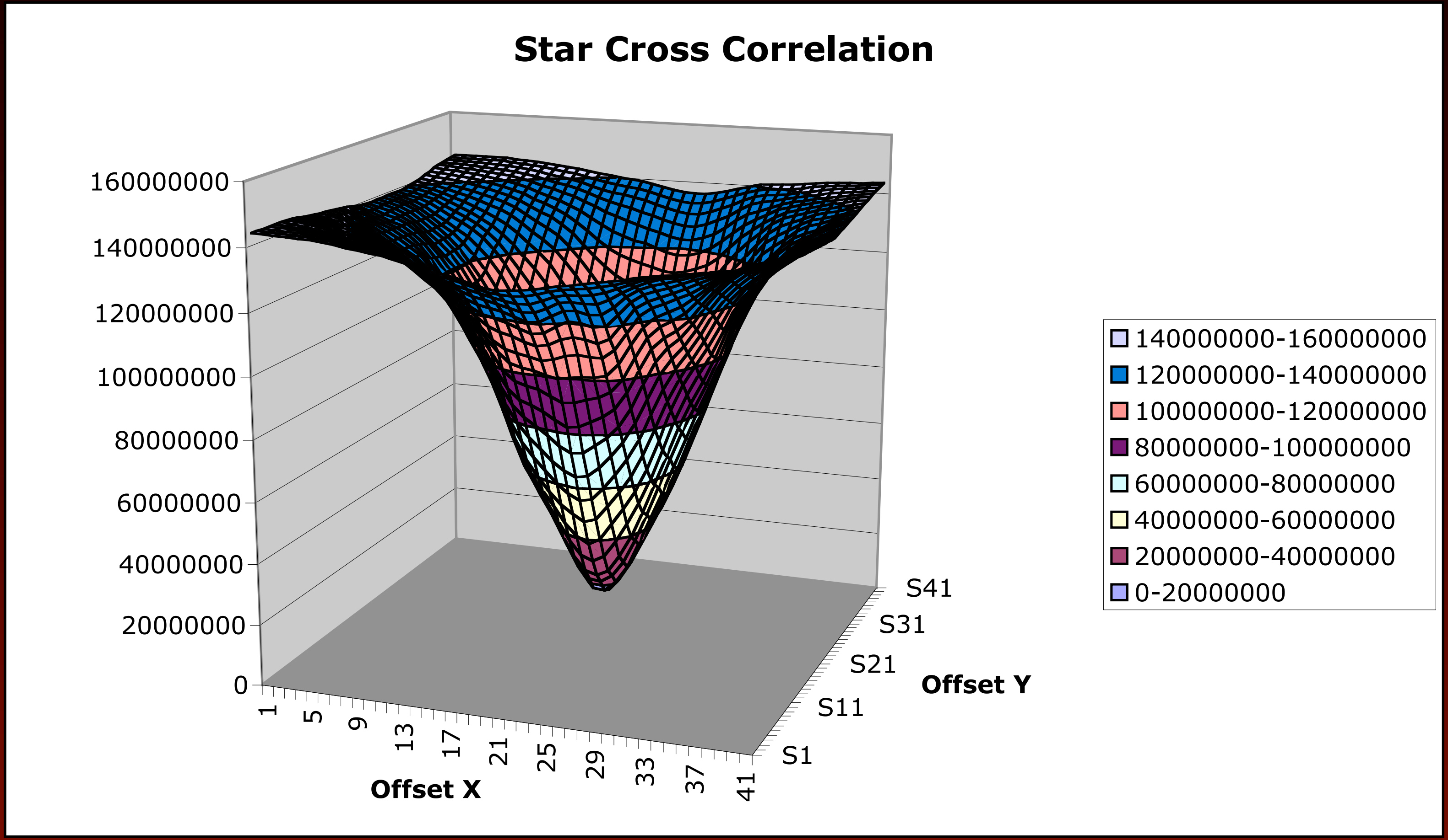
Courtesy of *European Southern Observatory*



- Reference image is a bright galaxy
- Compared to shifted (+5, -5) version
- Search for local minimum will provide the correct translation vector
- Sub-pixel offset obtained by fitting a parabola to the cross-correlation signal in x and y, and looking for the minimum.

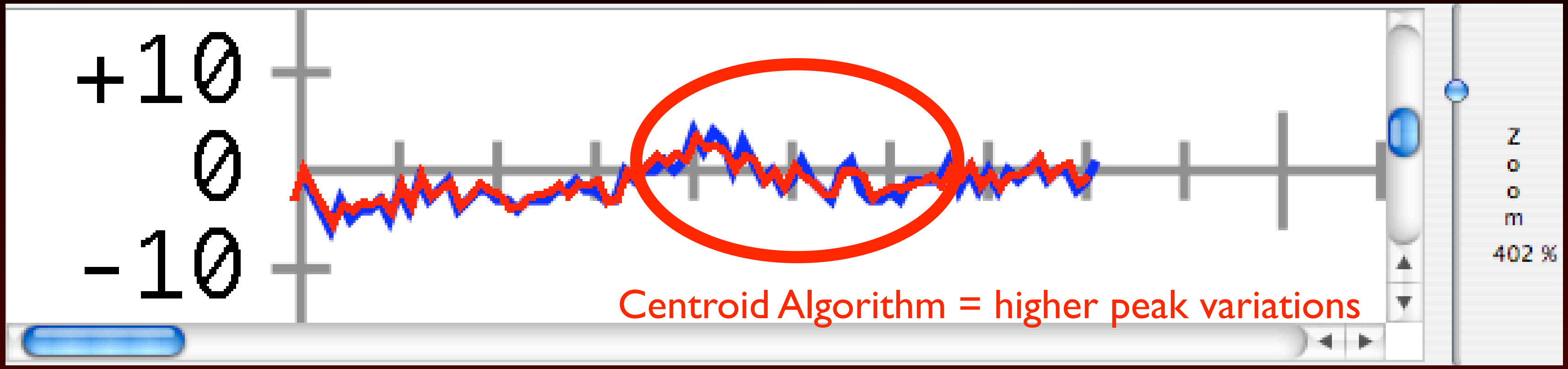
Cross Correlation Example

Single Star Image



ROI = 100 x 100
Search Area = +/- 20

Cross Correlation - test results

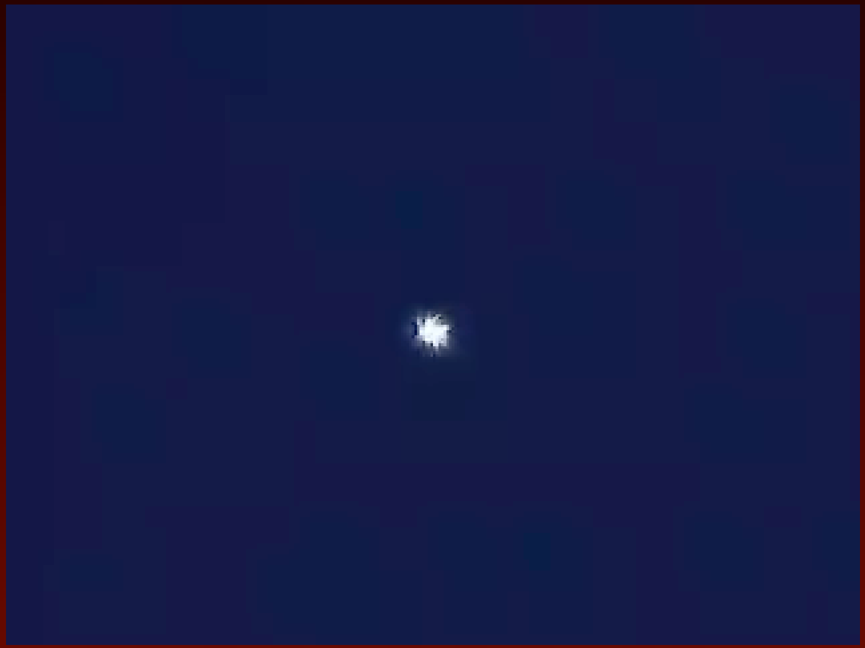


Centroid vs Cross Correlation (Results Overlay)

- Results from Quicktime movie of a 6 second image sequence. The movie was of a single star taken on a night of very poor seeing conditions.
- Centroid algorithm had (slightly) higher peak-to-peak variations in position.
- Algorithm execution time:
  - Centroid = 4mS
  - Cross Corr = 13,317mS (ROI = 100 x 100, Search Area = +/- 20)

Note: 1.33GHz powerbook used in test

Noisy Star Images from WebCams



- WebCam Image at 15 fps
- High background noise is typical of WebCams
- High 'star noise' due to fast integration times and atmospheric turbulence.
- Remedy:
    - integrate longer (camera)
    - average frames (fcGuide)

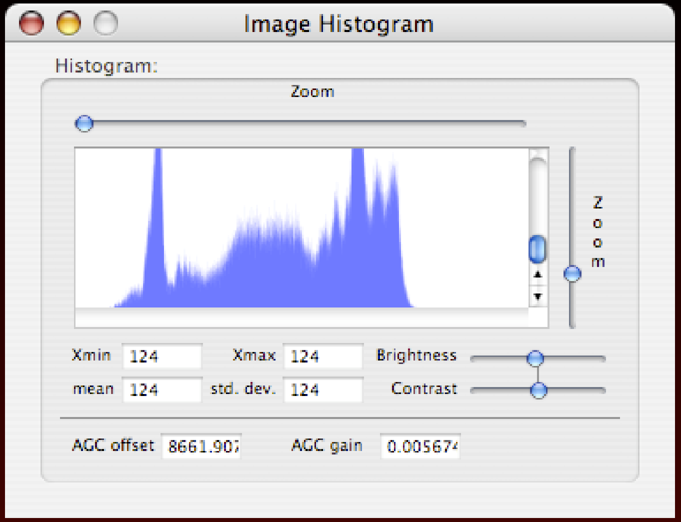
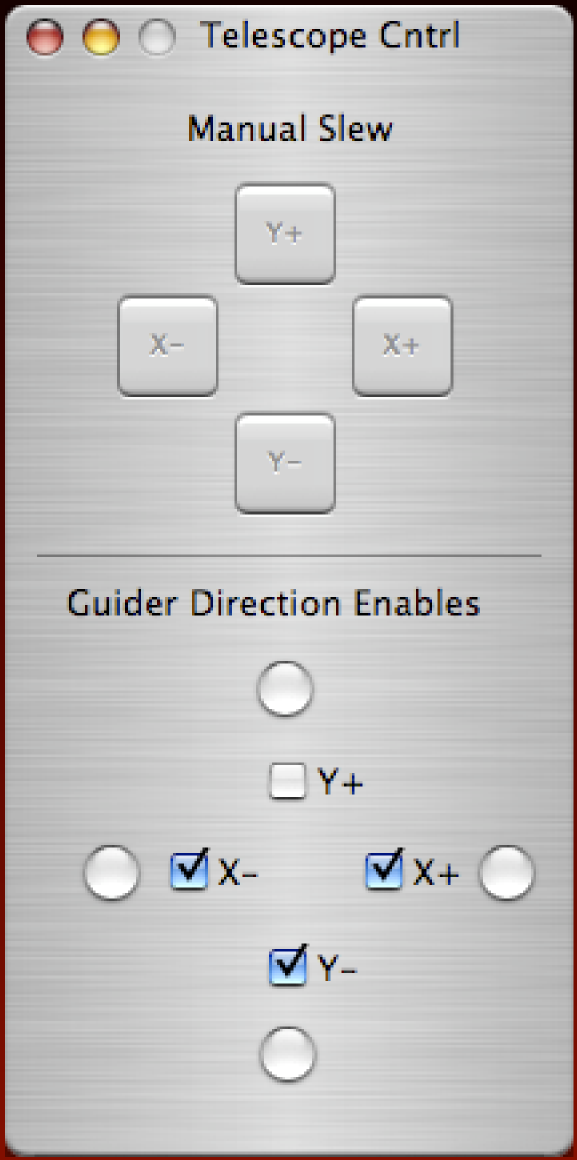


Image Histogram Window

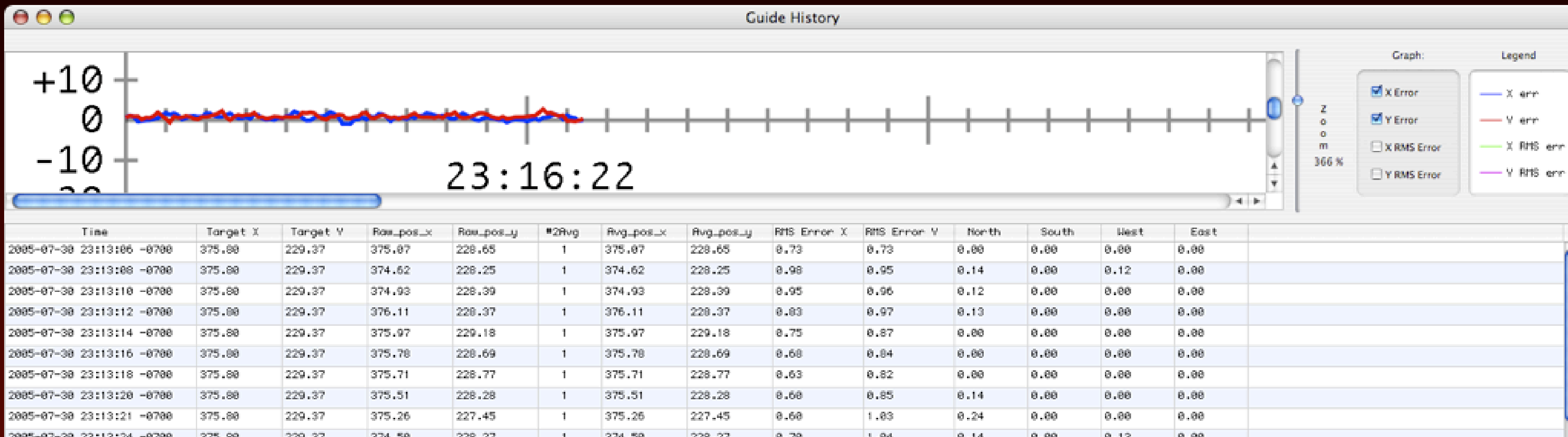
- Shows the real-time histogram for the full image frame
- Independent zoom controls on H and V
- Image statistics:
  - Max / Min
  - Mean
  - Standard Deviation
- Automatic histogram stretch (AGC) based on Mean and 2X Std. Dev.
- Manual tweak of brightness / contrast

Telescope Control



- Manual slew of telescope mount
- Guider status LED’s
- Individual enables for the four guide directions
    - useful for situations like excessive backlash

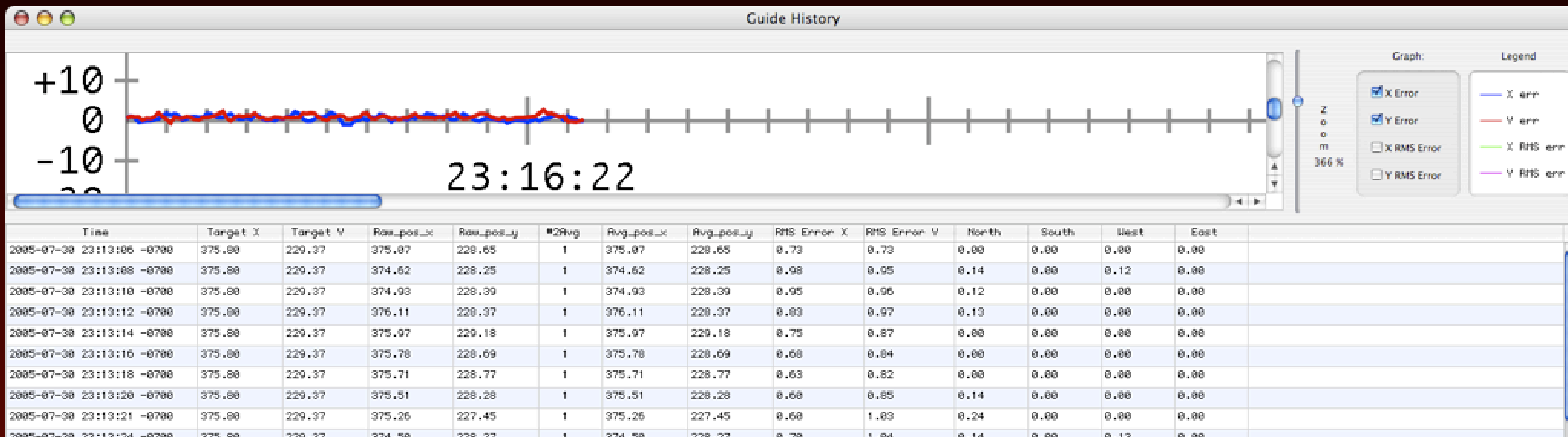
History Log Window



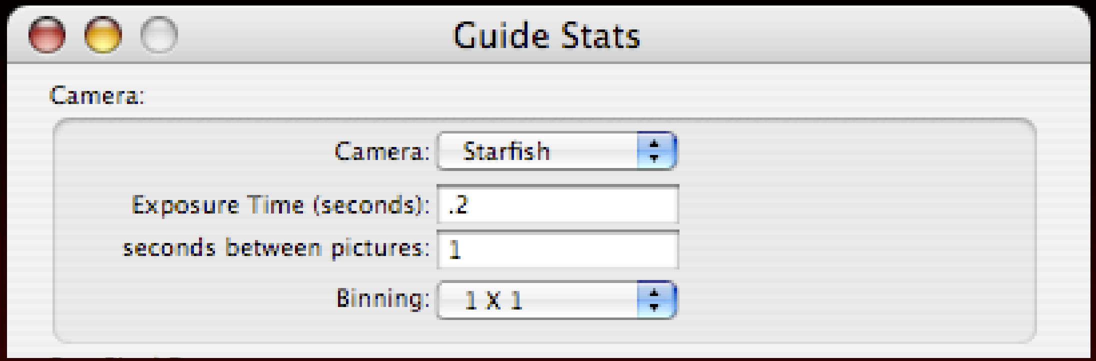
Time	Target X	Target Y	Raw_pos_x	Raw_pos_y	#2Avg	Avg_pos_x	Avg_pos_y	RMS Error X	RMS Error Y	North	South	West	East
2005-07-30 23:13:06 -0700	375.80	229.37	375.07	228.65	1	375.07	228.65	0.73	0.73	0.00	0.00	0.00	0.00
2005-07-30 23:13:08 -0700	375.80	229.37	374.62	228.25	1	374.62	228.25	0.98	0.95	0.14	0.00	0.12	0.00
2005-07-30 23:13:10 -0700	375.80	229.37	374.93	228.39	1	374.93	228.39	0.95	0.96	0.12	0.00	0.00	0.00
2005-07-30 23:13:12 -0700	375.80	229.37	376.11	228.37	1	376.11	228.37	0.83	0.97	0.13	0.00	0.00	0.00
2005-07-30 23:13:14 -0700	375.80	229.37	375.97	229.18	1	375.97	229.18	0.75	0.87	0.00	0.00	0.00	0.00
2005-07-30 23:13:16 -0700	375.80	229.37	375.78	228.69	1	375.78	228.69	0.68	0.84	0.00	0.00	0.00	0.00
2005-07-30 23:13:18 -0700	375.80	229.37	375.71	228.77	1	375.71	228.77	0.63	0.82	0.00	0.00	0.00	0.00
2005-07-30 23:13:20 -0700	375.80	229.37	375.51	228.28	1	375.51	228.28	0.60	0.85	0.14	0.00	0.00	0.00
2005-07-30 23:13:21 -0700	375.80	229.37	375.26	227.45	1	375.26	227.45	0.60	1.03	0.24	0.00	0.00	0.00
2005-07-30 23:13:24 -0700	375.80	229.37	374.50	228.27	1	374.50	228.27	0.70	1.04	0.14	0.00	0.13	0.00

- Spreadsheet view:
  - Time
  - Target position, Current Guide Star position
  - Filtered position
  - RMS error
  - Guide corrections
  - Data sorting

History Log Window

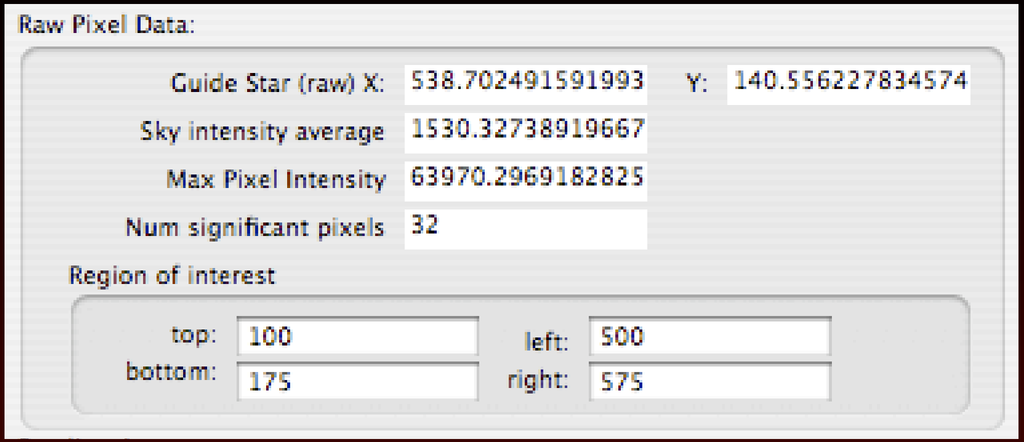


- Graph view
  - X Error, Y Error, RMS Error
  - Zoom
  - Annotated Axis



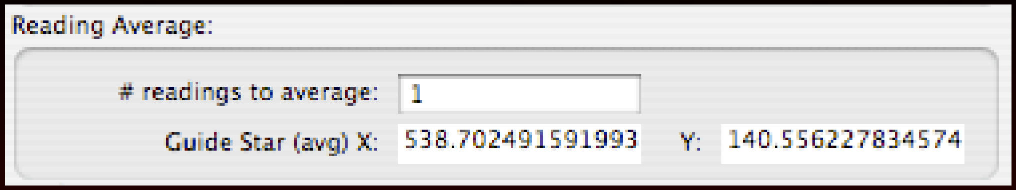
Guide Stats - Camera control panel

- Allows selection of camera to use
- User settable:
  - integration time
  - delay between pictures
  - binning modes



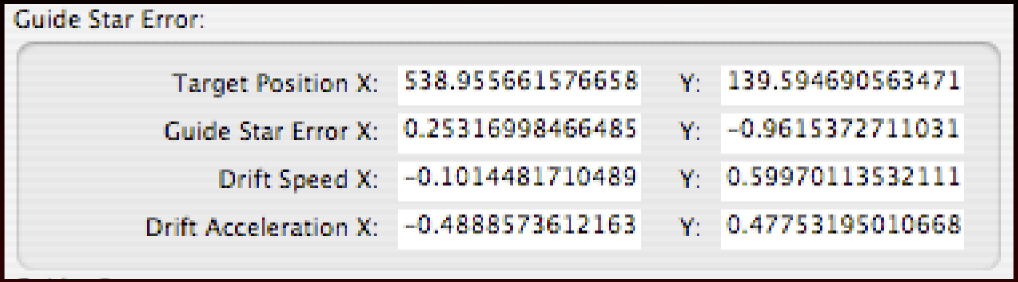
Guide Stats - Raw Image Data

- Shows:
  - Raw guide star position from Centroid Calculation
  - calculated ‘sky’ intensity of image background
  - Max Pixel intensity
  - Number of significant pixels used in centroid calculation
  - Region of interest mask coordinates



Guide Stats - Reading Average

- Allows user to specify the number of frames to average
- Produces a guide star position based upon this average.
- Useful in high noise conditions, high turbulence.
- Keep in mind that this slows effective capture frame rate
  - guider corrections cannot occur faster than capture rate

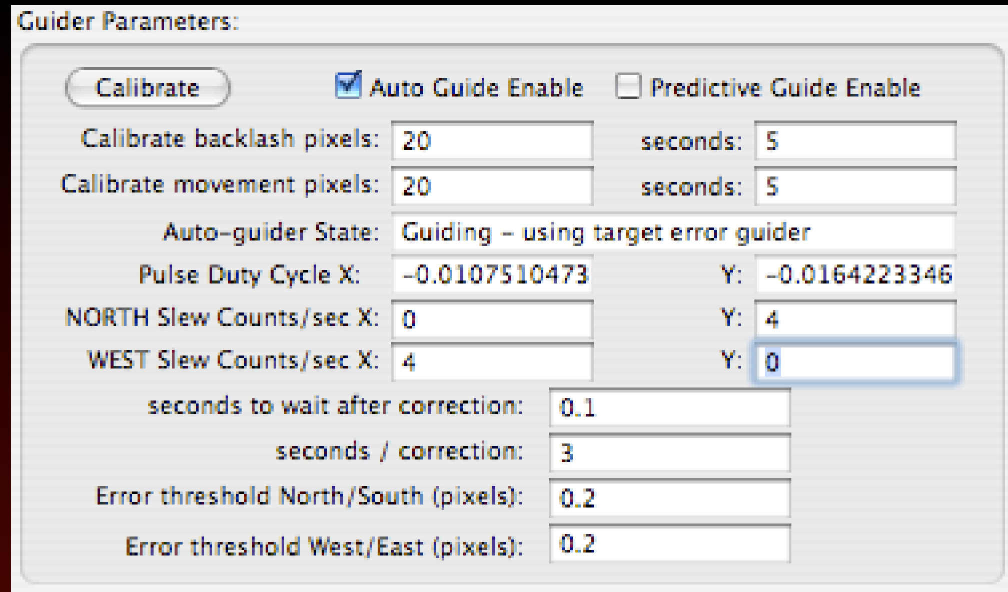


Guide Star Error:

	X		Y
Target Position X:	538.955661576658	Y:	139.594690563471
Guide Star Error X:	0.25316998466485	Y:	-0.9615372711031
Drift Speed X:	-0.1014481710489	Y:	0.59970113532111
Drift Acceleration X:	-0.4888573612163	Y:	0.47753195010668

Guide Stats - Guide Star Error

- Displays statistics of the guide star
  - target position
  - Guide star error (current - target)
  - drift speed / acceleration



Guide Stats - Guide Parameters

- Controls:
  - 'Calibrate' - starts calibration routine to characterize mount
  - 'Auto Guide Enable' - used to start / stop guiding
  - 'Predictive Guide Enable' - enables use of predictive guider

Guide Stats - Guide Parameters cont.

- Two types of guide algorithms used
    - Target error
    - Predictive Guider

- Target error guider makes corrections based solely on guide star positional error from reading to reading

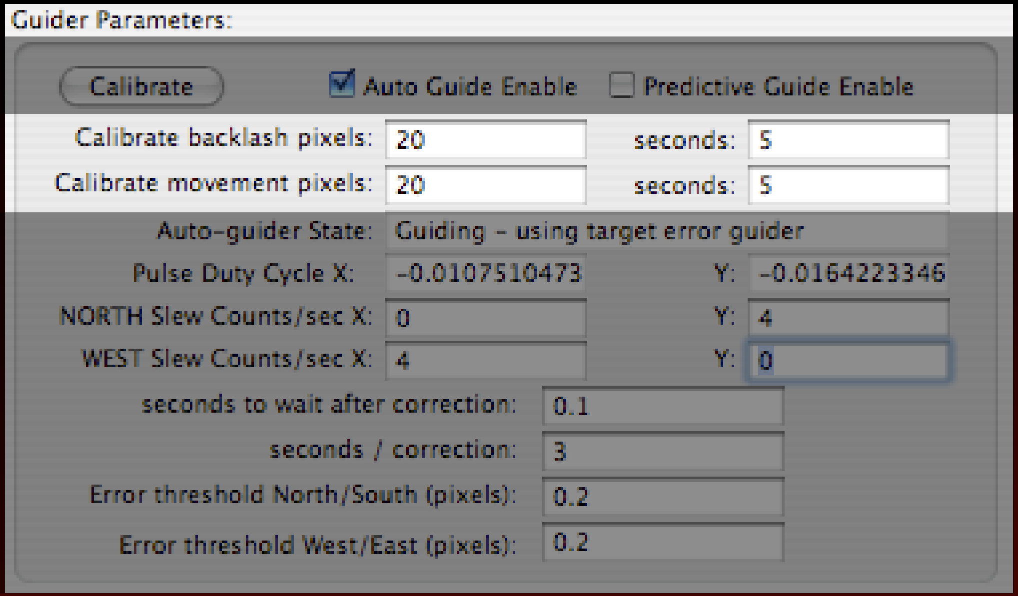
- Predictive guider makes smaller, more frequent corrections based upon past history

Guide Stats - Guide Parameters cont.

- Target Error Guider
  - Calculates guide star error based upon target and ‘averaged’ position
  - One correction made at interval specified
  - At least one new camera picture needs to be taken between corrections
  - Total error * Aggressiveness is made on each correction
  - user settable ‘aggressiveness’

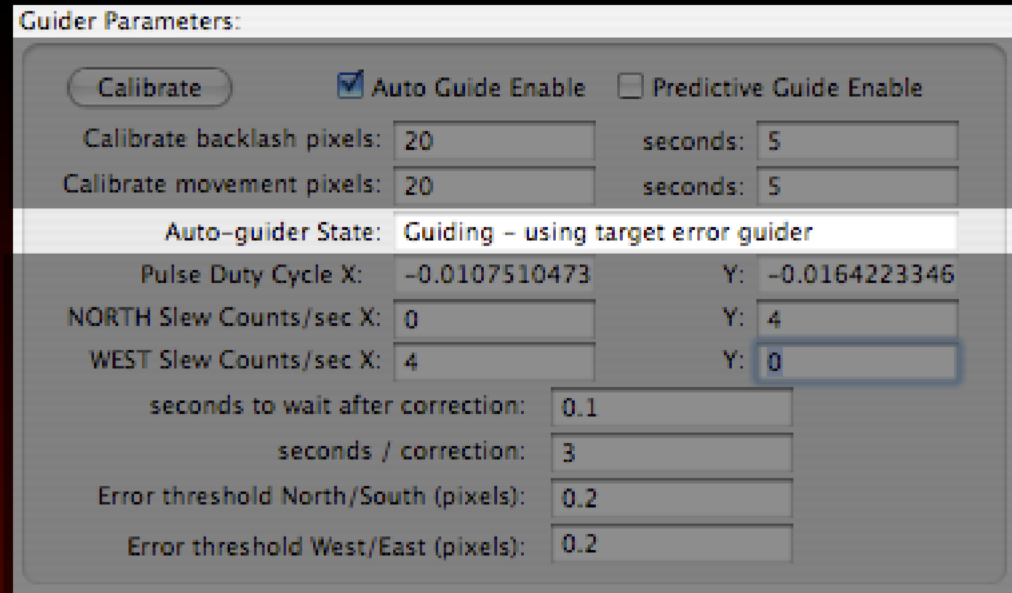
Guide Stats - Guide Parameters cont.

- Predictive Guider
  - analyses past history of guider
  - attempts to make to same absolute error corrections but with smaller more frequent corrections
  - error updates still made just as before
  - should result in smoother tracking in certain cases
  - useful for conditions such as large polar misalignment



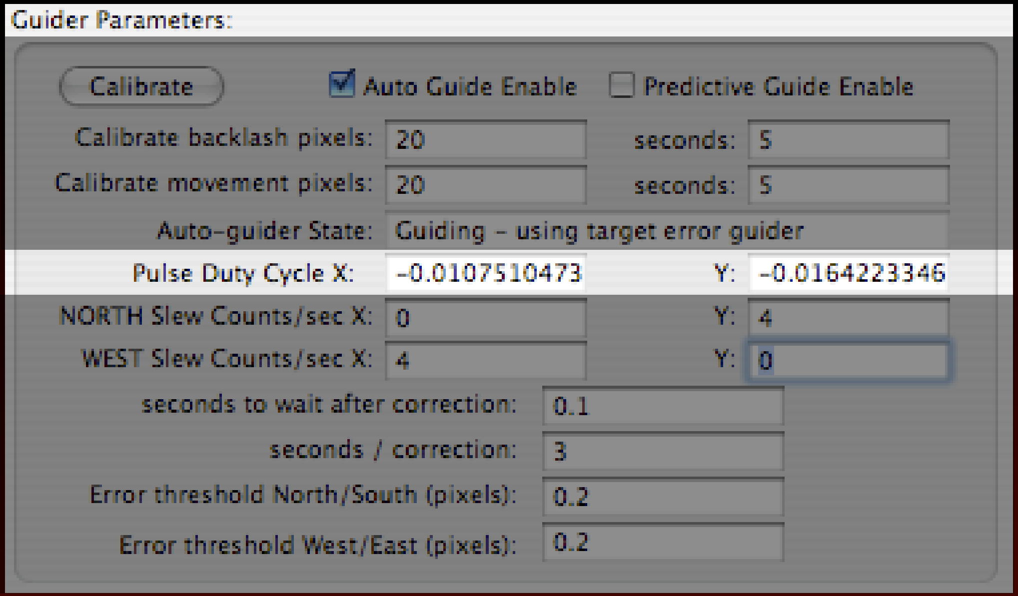
Guide Stats - Guide Parameters cont.

- Calibration Routine Parameters:
  - Minimum number of pixels to move
  - Minimum amount of time to move



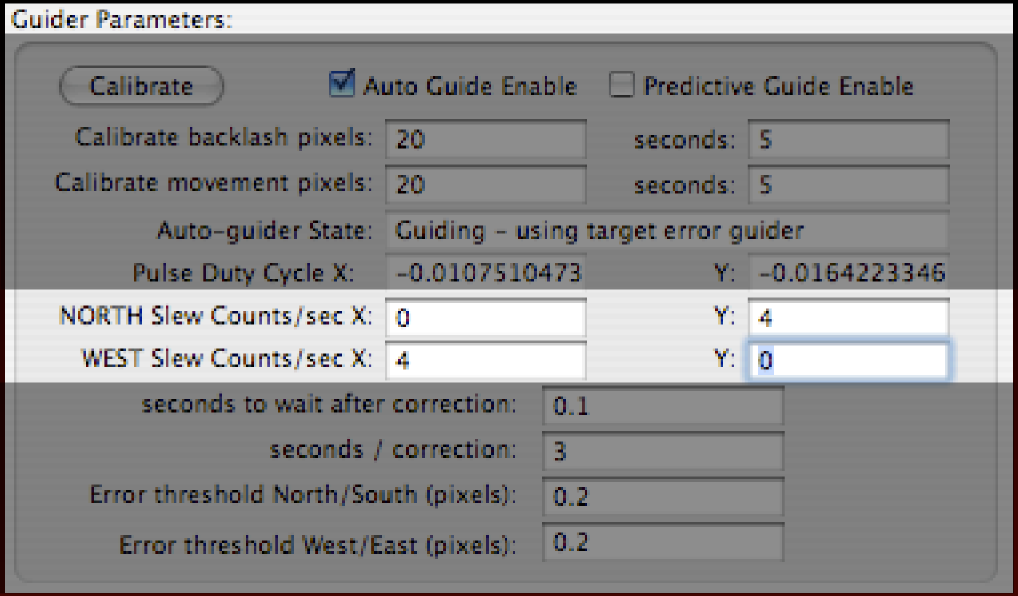
Guide Stats - Guide Parameters cont.

- Auto Guider State
  - Shows current state in state machine
  - Error messages displayed



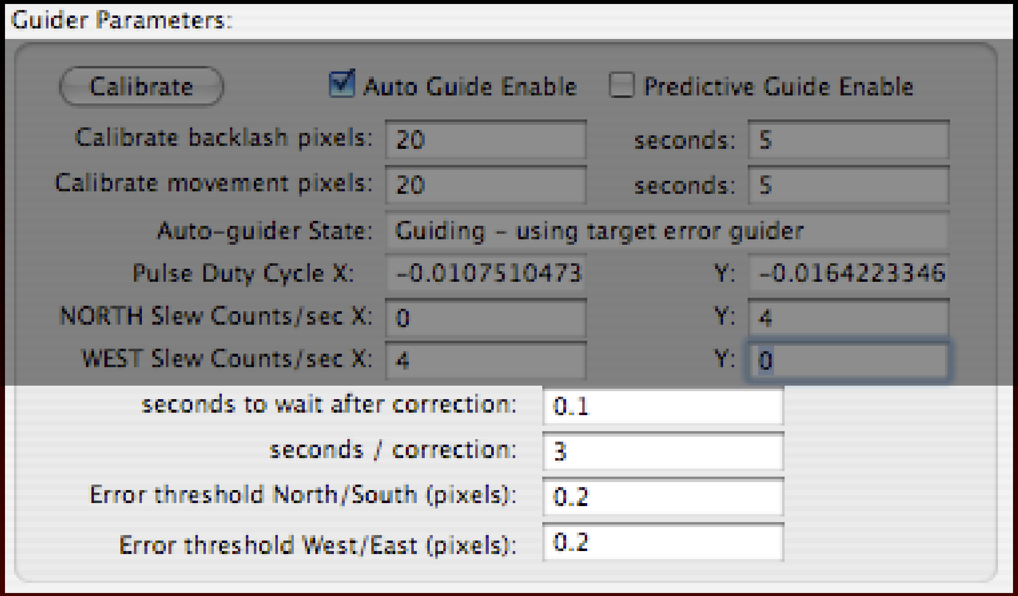
Guide Stats - Guide Parameters cont.

- Pulse Duty Cycle
  - historical average of the total guide time / idle time
  - low numbers indicitive of good inherent system tracking
  - high numbers indicative of amount of work necessary by the auto guider



Guide Stats - Guide Parameters cont.

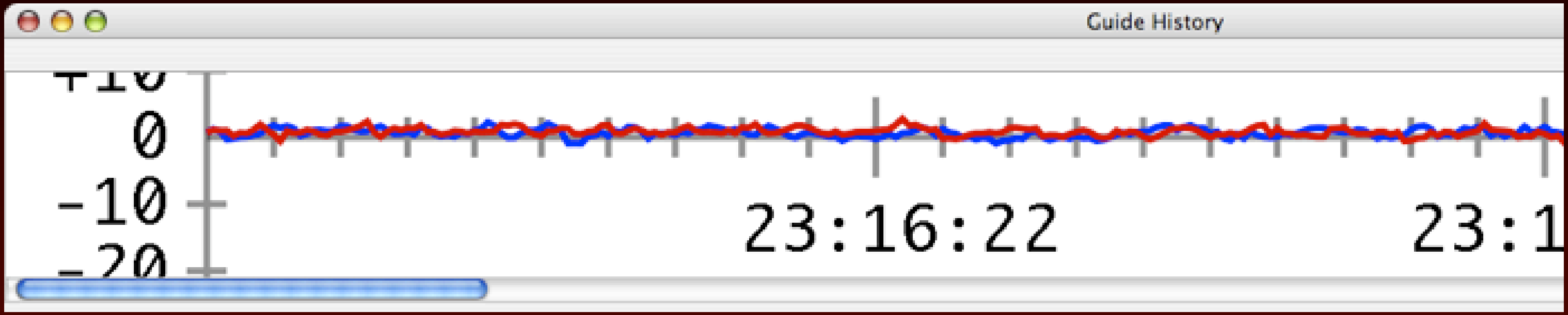
- Slew counts / sec
  - shows the amount of star positional change in pixels / sec of mount slew
  - low number indicate very fine positional changes when slewing
  - high numbers associated with long focal length guide scopes
  - measure of the degree of axis alignment between the guide camera and telescope mount axis



Guide Stats - Guide Parameters cont.

- User settable guide correction parameters
  - Frequency of correction
  - Delay after correction
  - Guide star error threshold

Guider Performance



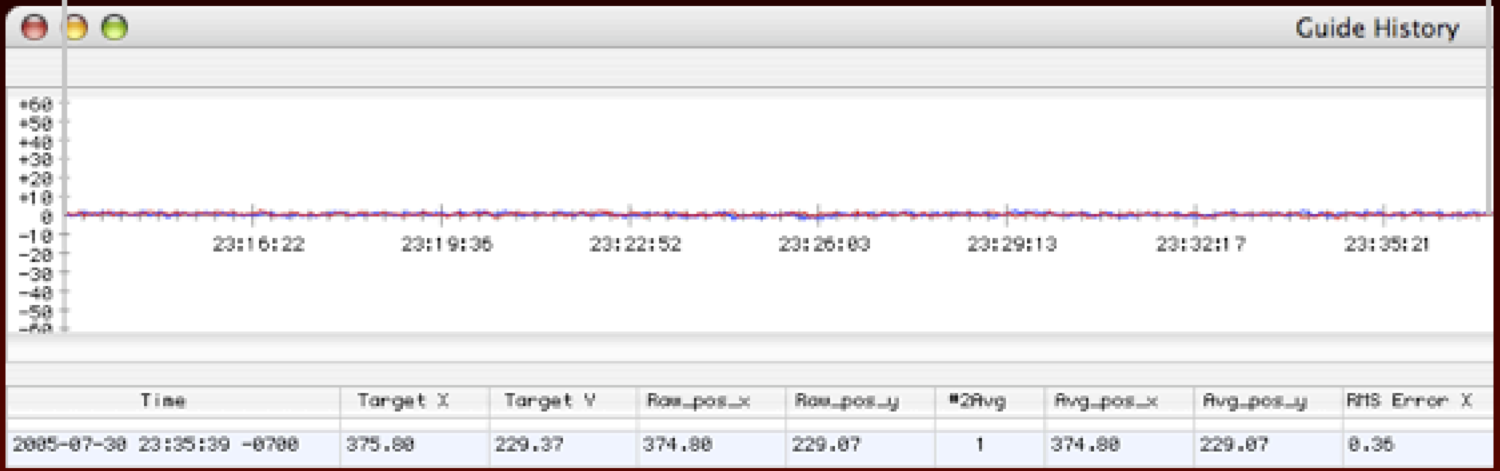
Target Error Guider

RMS Error X = 0.63 pixels
RMS Error Y = 0.78 pixels

Camera: ST402ME
Guide Scope: Takahashi FS-78 with vari-extender @ 2.1x. EFL = 1323mm

Guider Performance

23 minutes



Predictive Guider

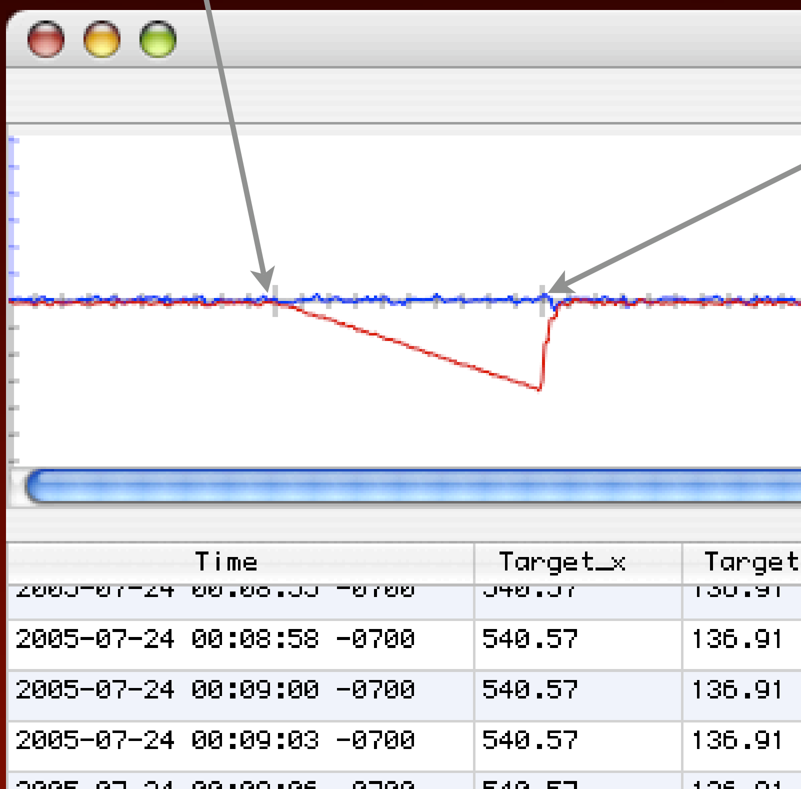
RMS Error X = 0.37 pixels
RMS Error Y = 0.29 pixels

Camera: ST402ME
Guide Scope: Takahashi FS-78 with vari-extender @ 2.1x. EFL = 1323mm

Guider Performance

Turn off ‘Y’ corrections

Re-enable ‘Y’ corrections

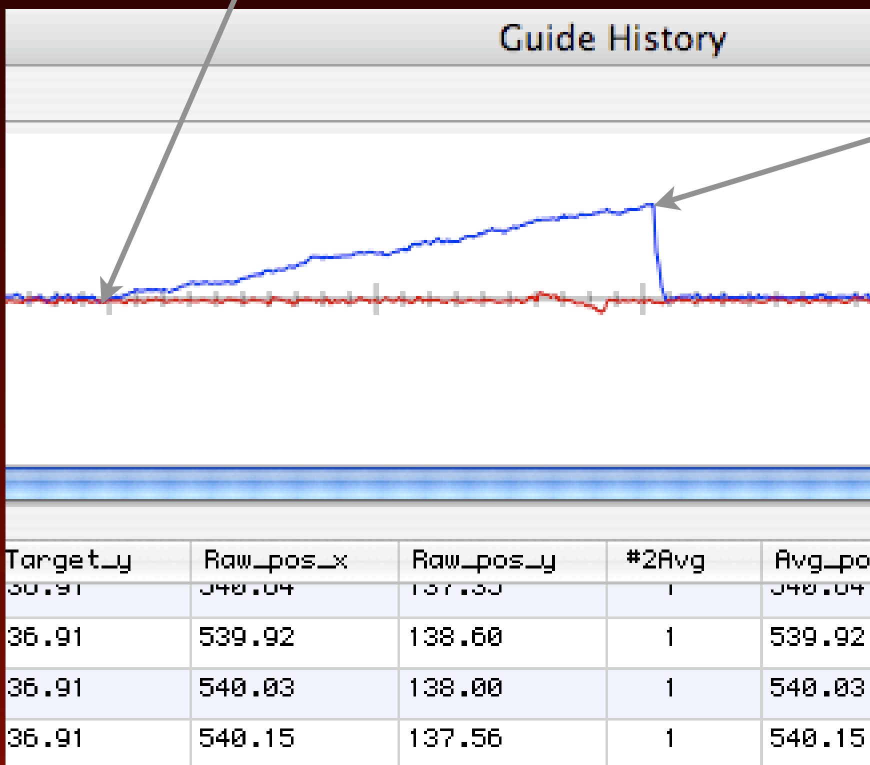


- Red trace is Declination drift

Guider Performance

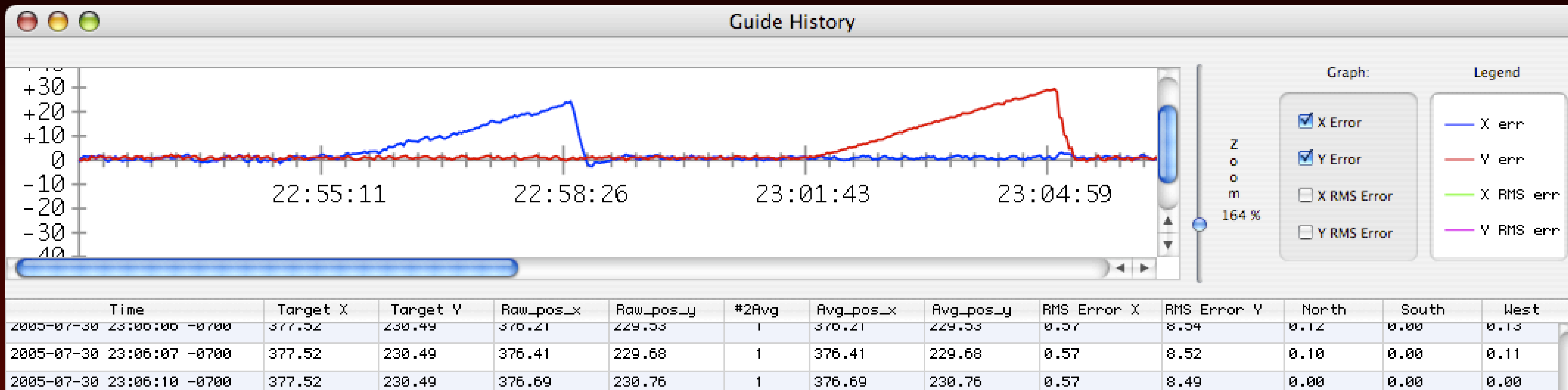
Turn off 'X' corrections

Re-enable 'X' corrections



- Blue trace is Right Ascension drift
- Non-linearity due to periodic and random errors in mount drive gears

Guider Performance

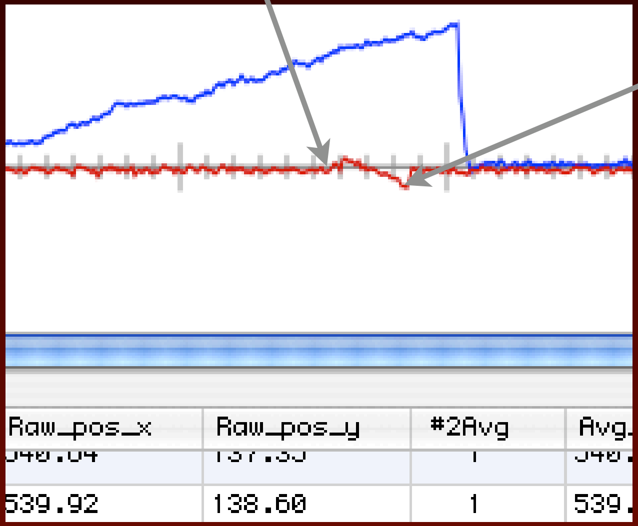


- Disable corrections to assess system performance
  - non-linearity in Right Ascension drift shows PEC
  - Slope of drift line will show degree of polar alignment

Guider Performance

over-correction

Backlash taken up again

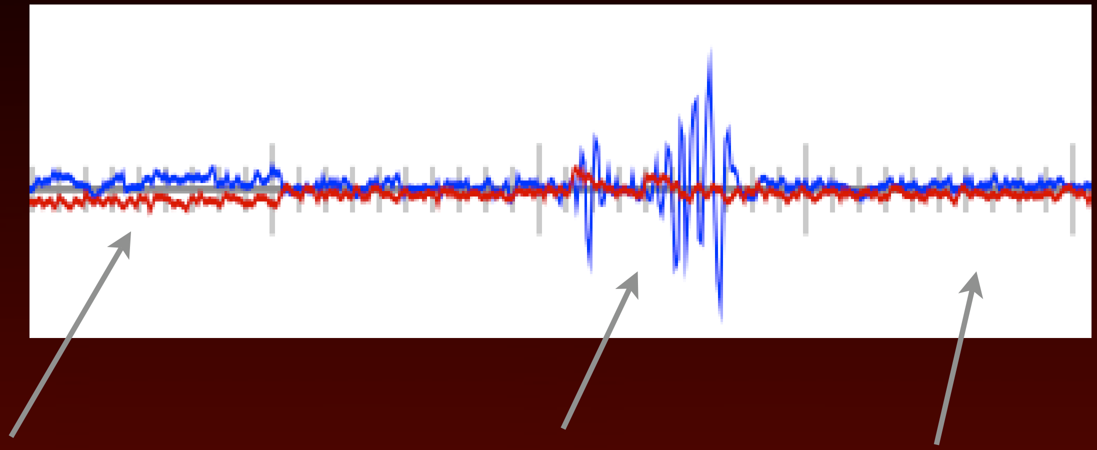


- Mounts with excessive backlash can have position overshoots.
- guider will make a ‘negative’ correction then over compensate the opposite direction until backlash is taken up
- Guide ‘enables’ useful to prevent this.
- Slope of line will be same as with auto guider disabled on that axis.

Guider Performance

- Guidescopes, and cameras add a lot of weight to the mount.
- Counterweights to balance the load will be necessary to achieve good results.

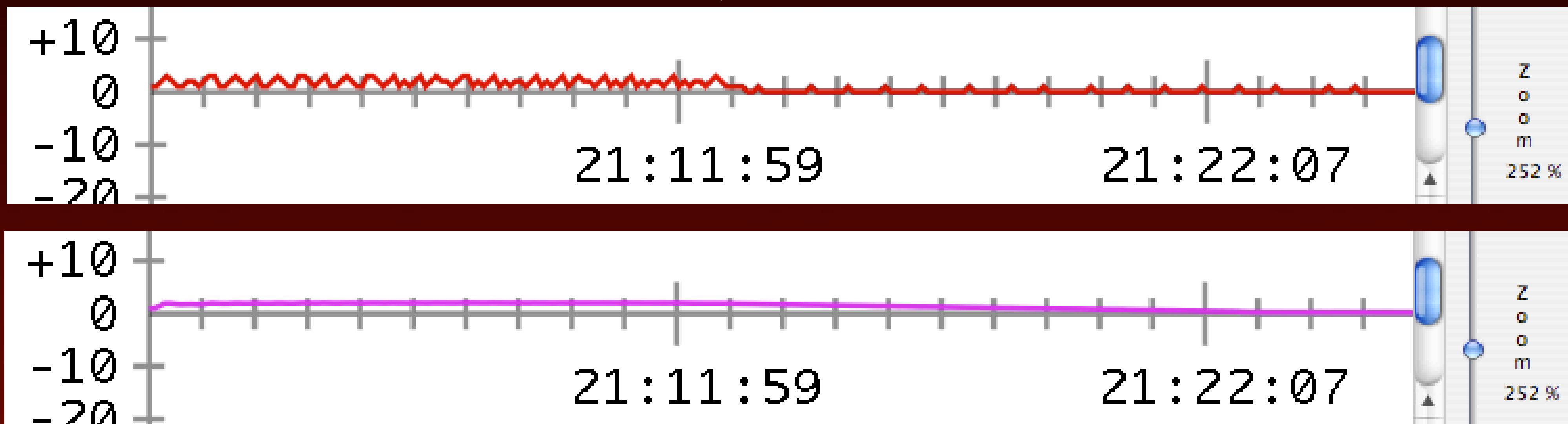
Guider Performance - aggressiveness



- High aggressiveness setting can cause the whole system to exhibit instability. Over-corrections will cause oscillations.
- Low setting will cause undue error.
- Optimal setting will allow guide star to more closely ‘hug’ the target position
- Determined by trial with calibration results used as a guide.

Guider Performance - Predictive Guider Results

Enable Predictive Guider



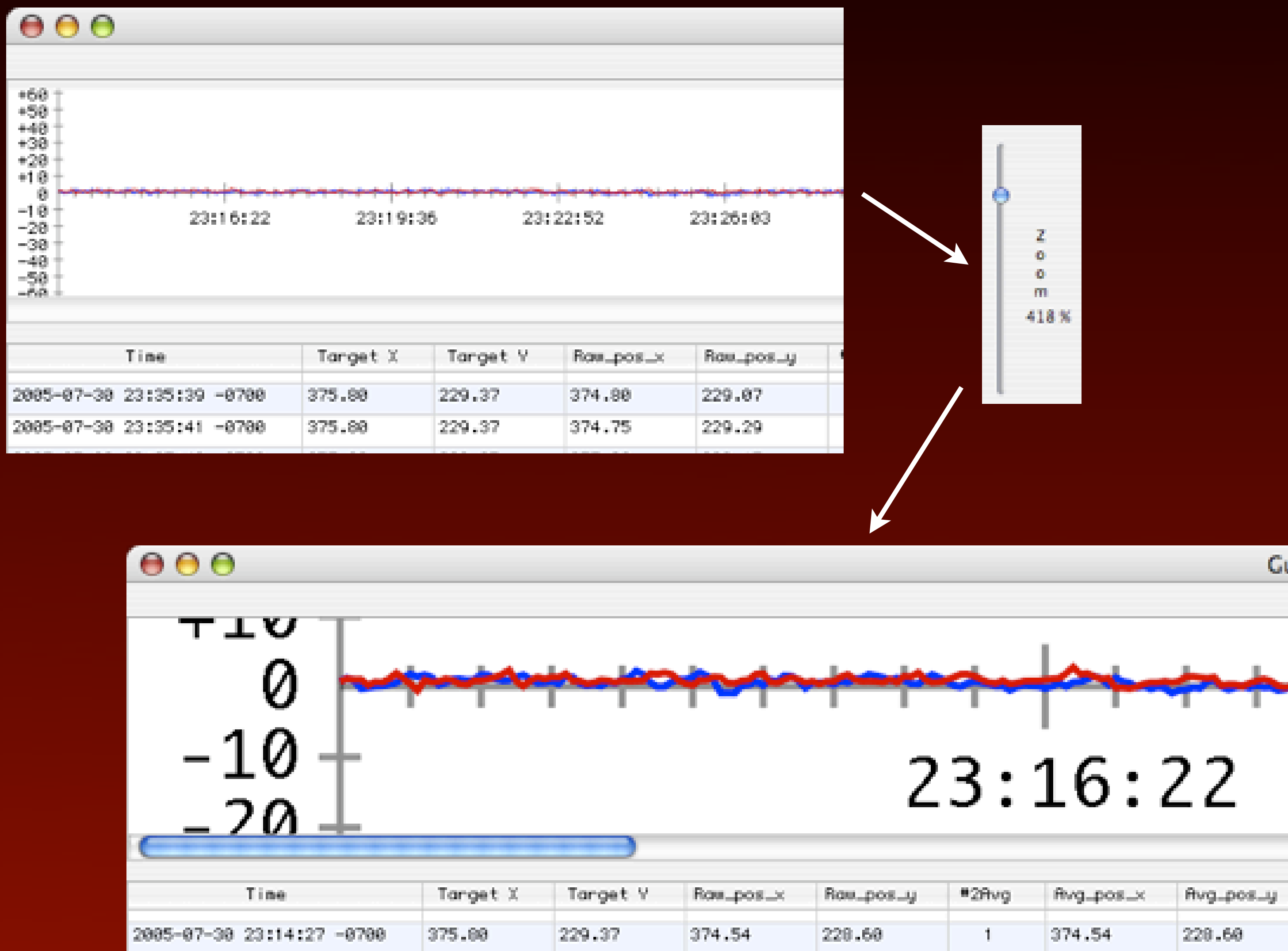
Target Error guider
> 2 pixels RMS

Predictive guider
< .27 pixels RMS

MacOS X Software Devlopment

- fcGuide is a Cocoa Application
- Written with XCode development tools
- GCC 4.0 Compiler
- Application framework
  - widgets
  - NSString, NSData, NSView, etc
  - ‘Bindings’ - link between View and Model
- Interface Builder

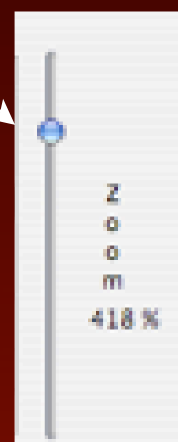
Zoom = 4 Lines of Code!



Power of 'Bindings'

Slider and Field in Synch = 0 Lines of Code!

Slider



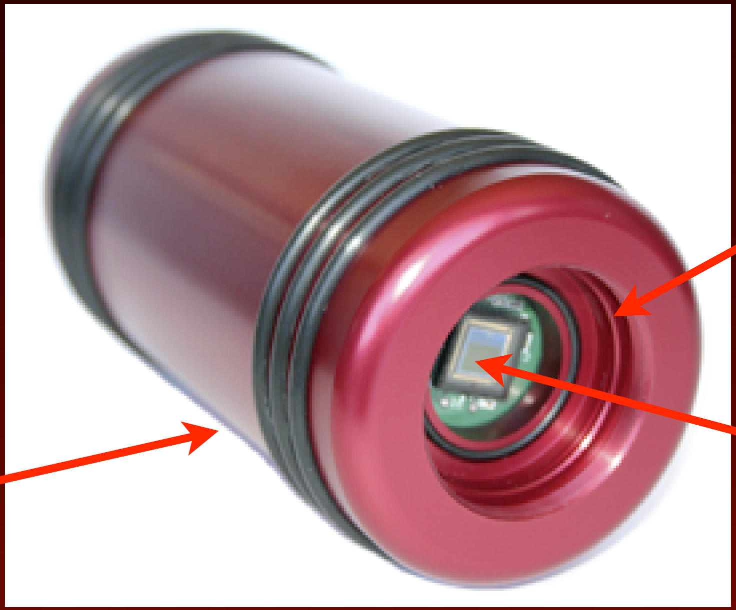
Zoom Scale Field

Companion Guide Camera

- 'STARFISH' dedicated guide camera
  - Use of 1/2" format CMOS sensor to allow aggressive pricing
  - small 3.2 u pixel size for good resolution
  - > 1.0 V/lux-sec (550nm) sensitivity
  - 61dB dynamic range
  - binning modes supported
  - fast frame rates with USB 2.0 interface for fast downloads
  - integration times from 1mS to one hour.
  - integrated ST-4 and RS-232 interfaces
  - On board 32 bit CPU and dedicated hardware image processing functions.

STARFISH Camera
Front

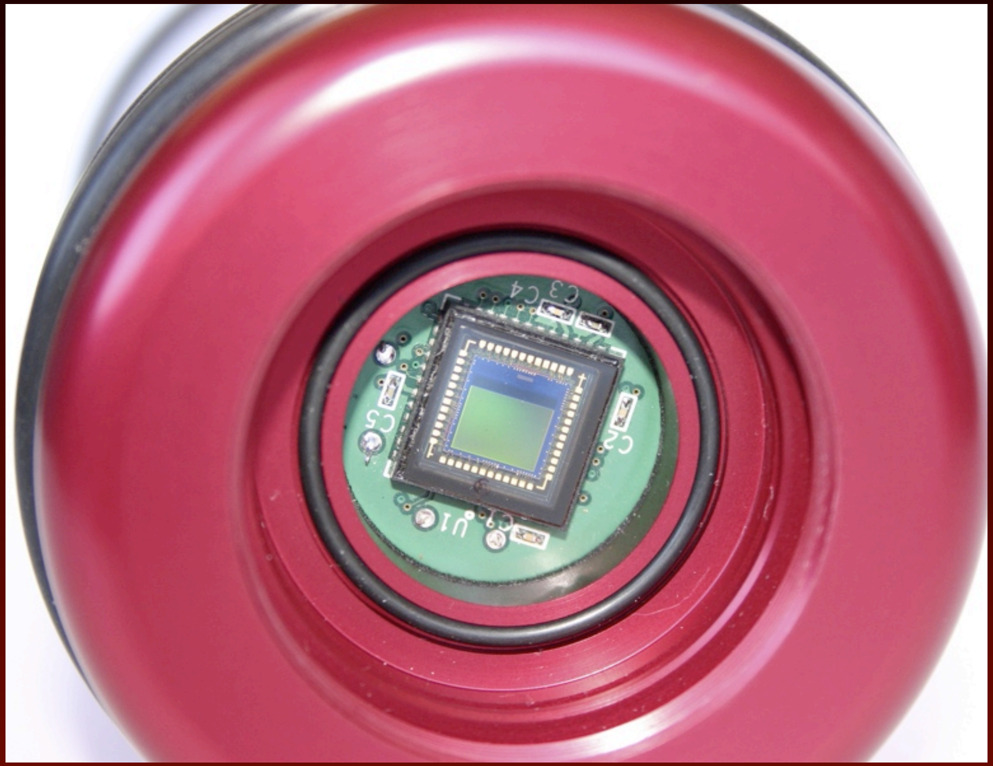
1/4 - 20
Mount



T-thread
Lens mount

Image Sensor

STARFISH Camera



3 MPixel CMOS Image Sensor

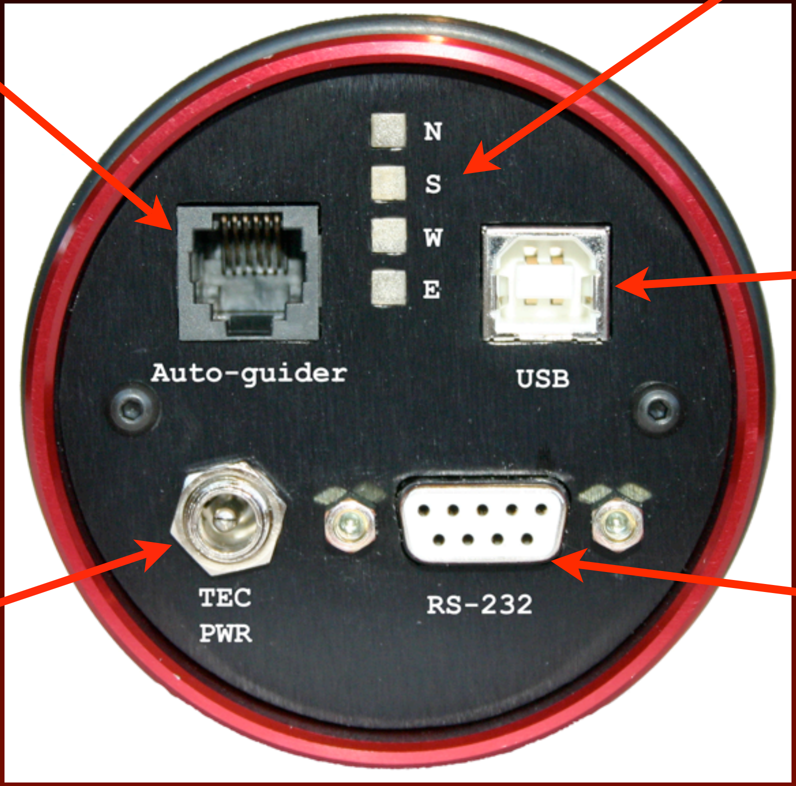
STARFISH Camera

Standard T-Threaded Optical Interface
(C-Thread Adapter Shown)

STARFISH Camera
Back

ST-4 Guider Port

Status LEDs



USB 2.0

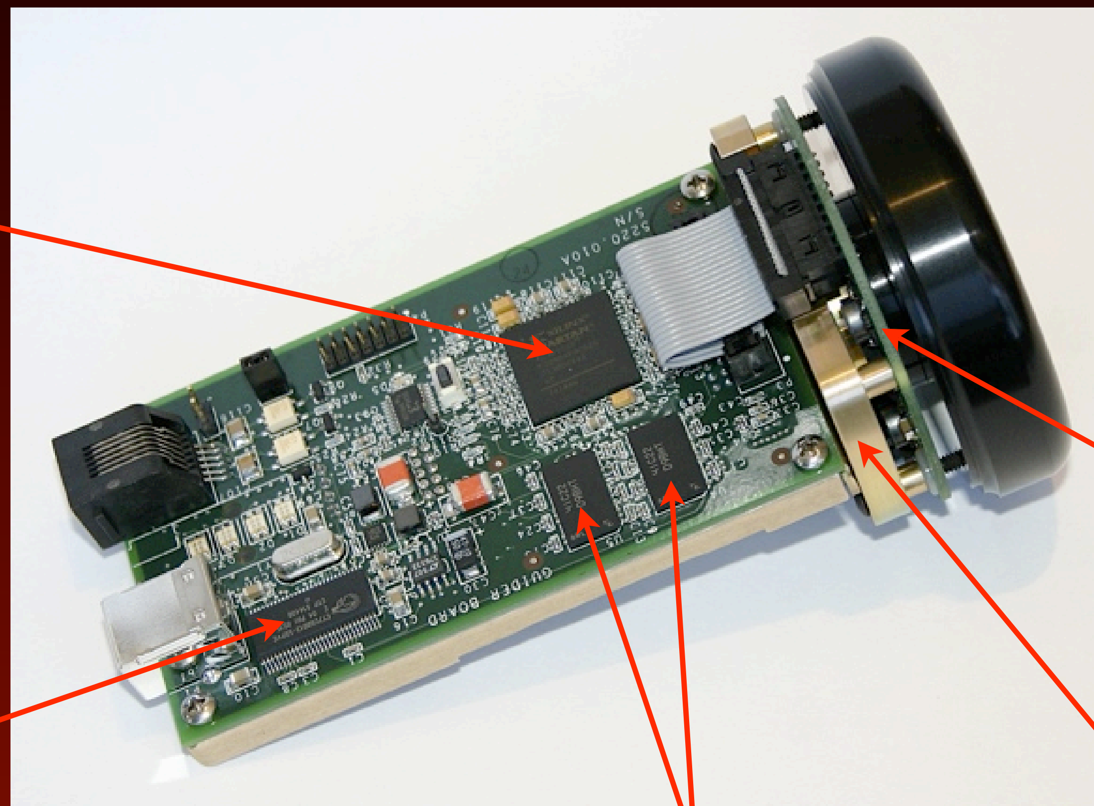
RS-232

TEC Cooler Power

STARFISH Camera

Little bigger than a 2" eyepiece

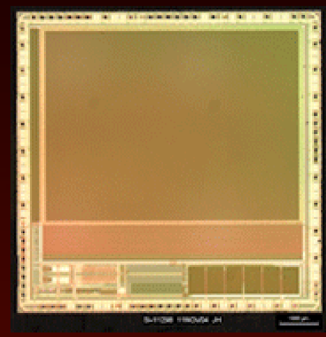
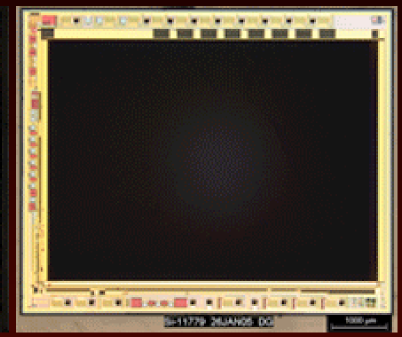
STARFISH Camera



'STARFISH' Image Sensor

- 3Mpixel CMOS
- Innovative design with a high fill factor pixel (effective transistors / pixel = 2.5)
- 1.0 V/lux-sec (550nm) sensitivity
- Double-poly process increases capacitance in 'hold' node. Results in lower noise

CMOS vs CCD

	Micron MT9T001	Panasonic MN39482
Pixels	3 Mpixel	4Mpixel
Technology	CMOS	CCD
Optical Format	1/2"	1/2.5"
Pixel Size	3.2u	2.5u
Pixel Capture Area	5.0u	1.2u
Fill Factor	60%	20%

CPU

- 32 Bit RISC Architecture
- 64 MByte DDR SDRAM
- USB 2.0 - host computer interface
- RS-232 - filter wheels, mount communication
- Software downloads via USB
- Auto-guider pulse generator in hardware
- Sensor TEC cooler regulation

Image Processor

- Integrated frame grabber / buffer
- 1mS resolution on exposure timing
- Frame buffer memory shared with CPU
- Hardware acceleration of image processing functions

Image Processor Hardware Acceleration

Internal Hardware acceleration is built into the camera's architecture. The following acceleration algorithms are planned

- Image histogram
- Image mean, std/dev.
- Image Demosaicing
- Image Monochrome Conversion
- Image Calibration
- Frame Averaging

Software Support

- MacOS X
  - fcGuide
  - fcCapture
  - iCCD (planned)

- Windows
  - Drivers for MaxIm DL, CCDSoft

- SDK for users desiring to write their own applications

Starfish Camera Availability

- Beta field tests begin October
- Production shipments December
- Target price = < $900

- Announcement list signup:
  http://www.fishcamp.com

fcGuide

- Poll:
  - http://www.fishcamp.com
- Gauge commercial interest in unbundled application
- Feature set:
  - camera support
    - Web-cams, astro-cams
  - telescope interface
    - serial interface
    - relay box

Summary

- fcGuide Mac Application:
  - camera support
    - web-cams
    - astro-cams
  - Advanced feature set
    - Guide algorithms
    - history logs, performance statistics
- ‘Starfish’ Astro-camera
  - Integrated guiding solution
  - versatility to be used as an imaging camera
  - hardware acceleration for image processing functions
  - commercial availability Q4 2005.