Corner Rafts

LSST Camera Workshop
SLAC
Sept 19, 2008

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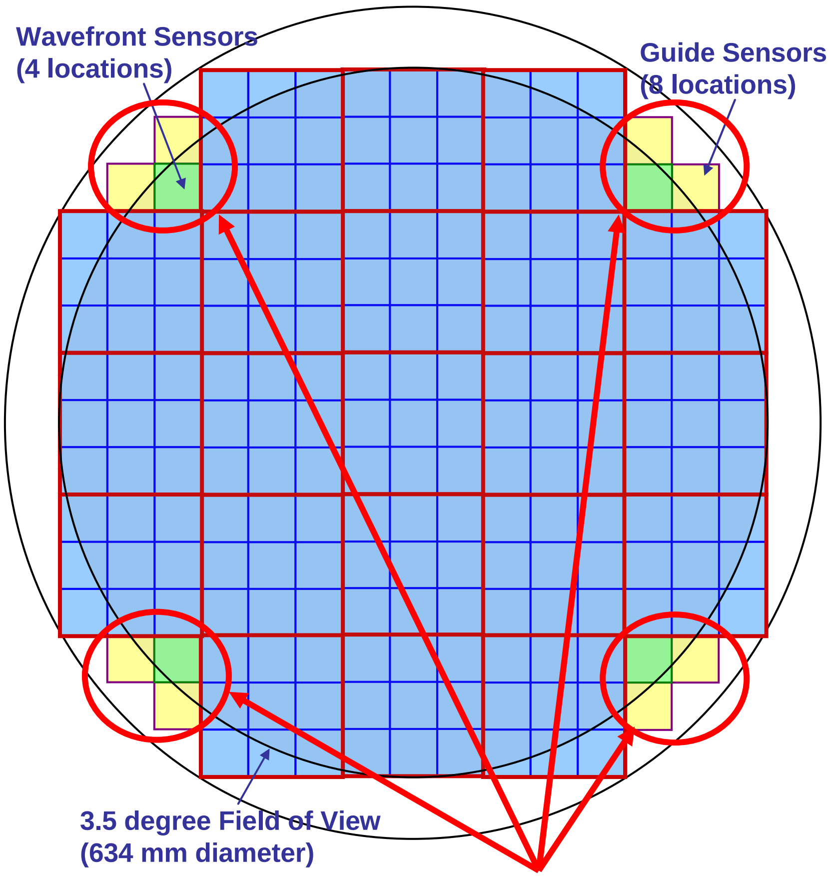
Corner Raft Session Agenda

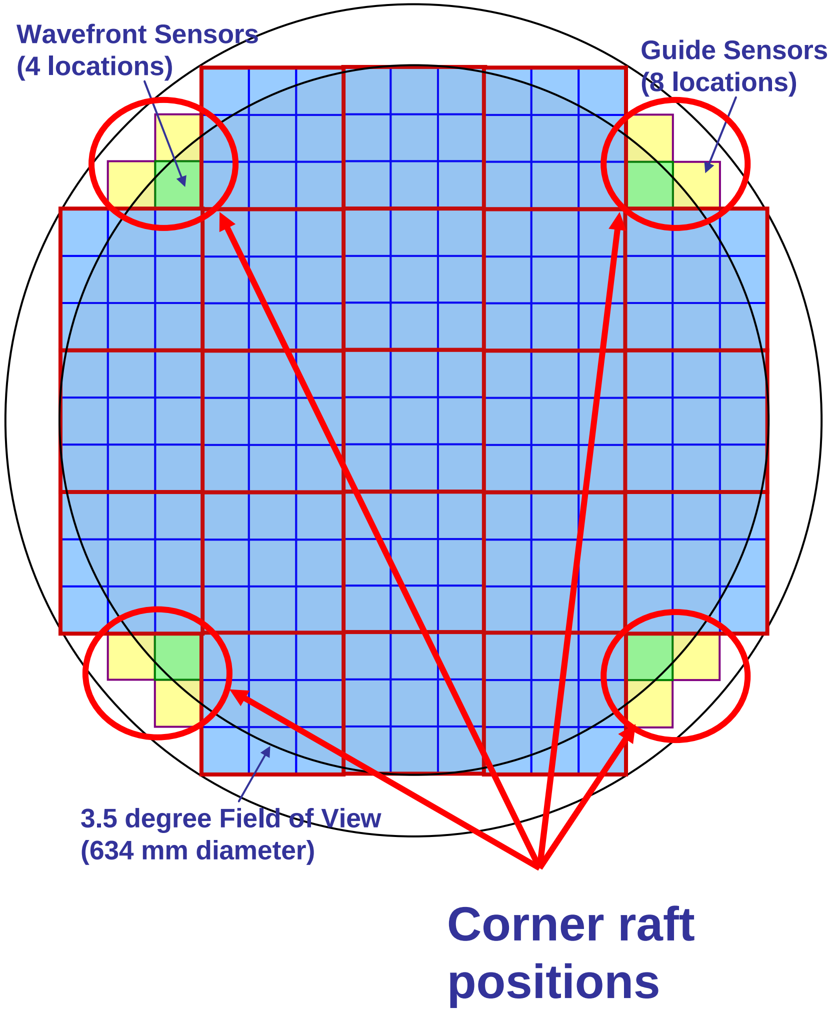
1. System Engineering
   1. Tolerance analysis
   2. Requirements flow-down
   3. Prototype testing
2. Current plan and schedule for delivery to I&T
   – Corner raft mechanical system (Purdue)
   – WFS detector (Brookhaven)
   – WFS FEE (U. Penn.)
   – WFS BEE (Harvard)
   – WFS DAQ and control (SLAC)
   – Guider detector (RIT)
   – Guider FEE and BEE (LLNL)
   – Guider DAQ and control (LLNL-SLAC)
   – Guider image processing (LLNL)
3. Key technical milestones
4. Highlight specific technical development activities
   1. Corner raft mechanical design and thermal analysis
   2. Guider image processing analysis
   3. Guider detector testing
5. Test requirements/equipment at each phase
6. Task interdepencies with other subsystems
7. What is the subsystem, self-protection plan/features



Corner raft positions

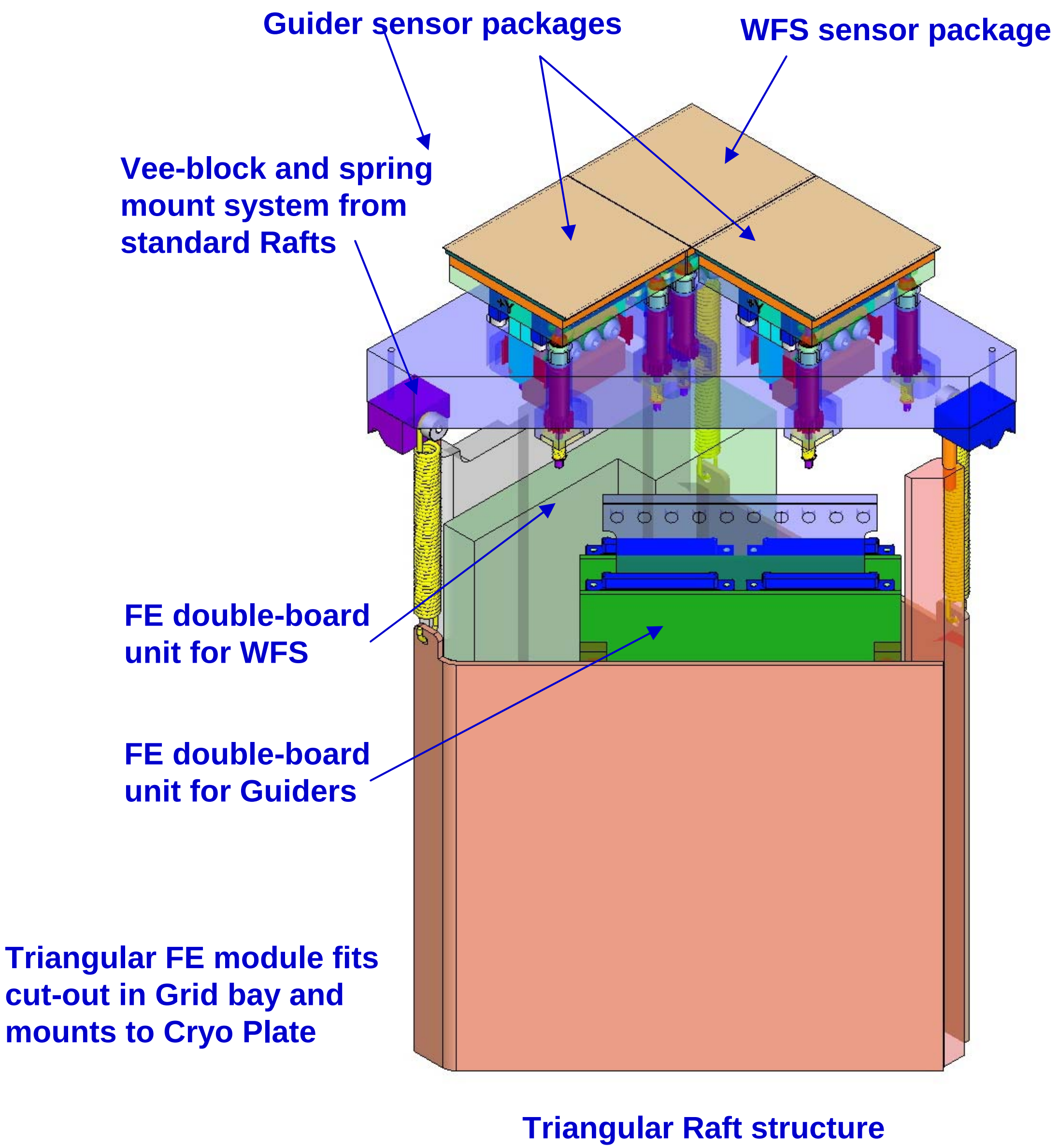
Corner Raft Assemblies: Reference Design

- **Four corner rafts are located in the corners of the focal plane**
  - **Corner rafts contain wavefront sensors and guide sensors**
  - **Wavefront sensors are located in the single inner position, nearest the center of the focal plane, with an area equivalent to one science detector**
  - **Guide sensors are located in the two outer positions, farthest from the center of the focal plane, each with an area equivalent to one science detector**



Corner Raft Tower Concept (Nordby, Guiffre)

- Mechanical and thermal design of the corner rafts is as similar as possible to the science rafts
- Electronics for operating the wavefront sensors and guide sensors are packaged within the corner raft volume behind the detectors, similar to the science raft configuration
- Data acquisition and control for the wavefront and guide sensors are managed using the same infrastructure as for the science detectors



Wavefront Sensors

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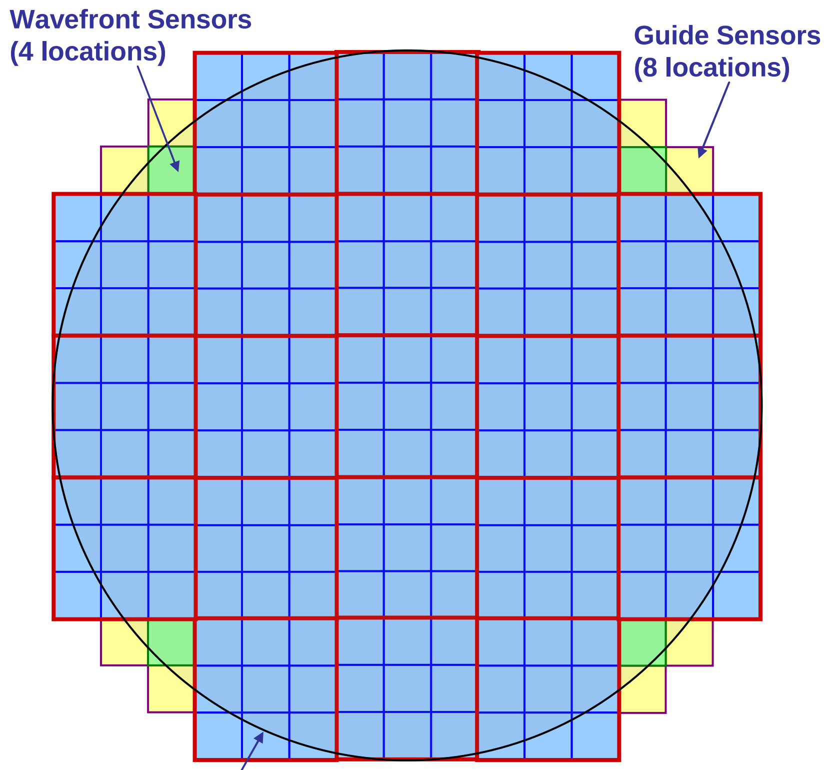
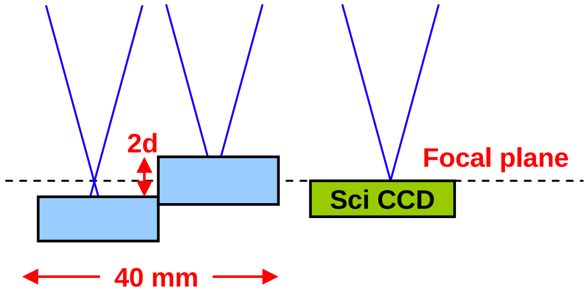
Wavefront Sensors Assemblies: Reference Design

- Four wavefront sensors are located in the corners of the focal plane
  - Tomographic wavefront reconstruction algorithm developed for LSST was used to evaluate the placement of wavefront sensors
  - Four wavefront sensors in a square arrangement were found to be adequate to meet requirements

- Wavefront sensors are curvature sensors
  - Measure the spatial intensity distribution equal distances on either side of focus
  - The phase of the wavefront is related to the change in spatial intensity via the transport of intensity equation
  - The phase is then recovered by solving this equation



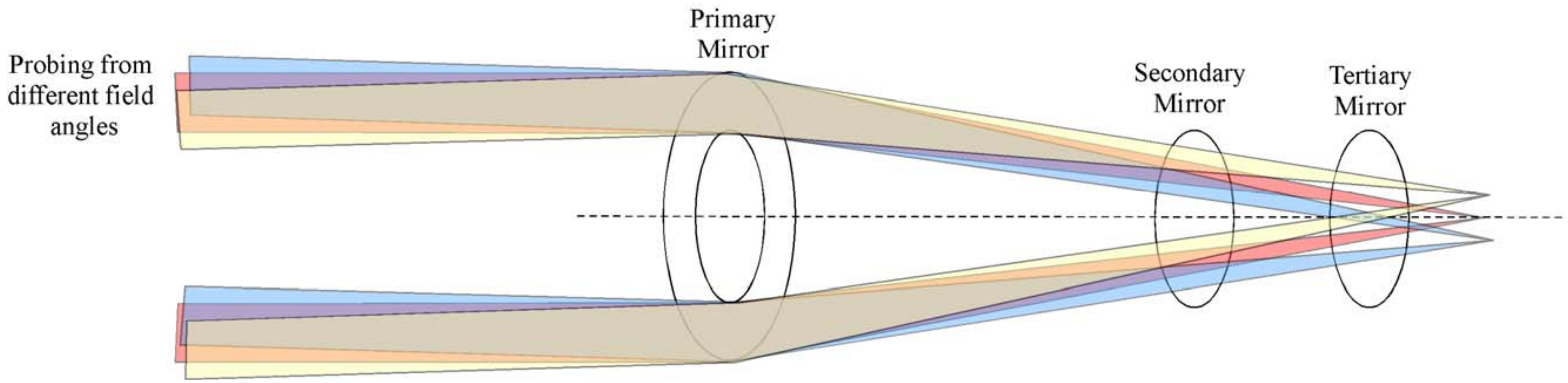


Curvature Sensor Side View Configuration

Tomographic wavefront reconstruction

Large Synoptic Survey Telescope

- **Collecting wave-front data from stars located at different field angles enables a tomographic reconstruction of the mirror aberrations.**
- **The tomographic problem can be reduced to a matrix problem by assuming an annular Zernike expansion of aberrations at each of the mirror surfaces.**

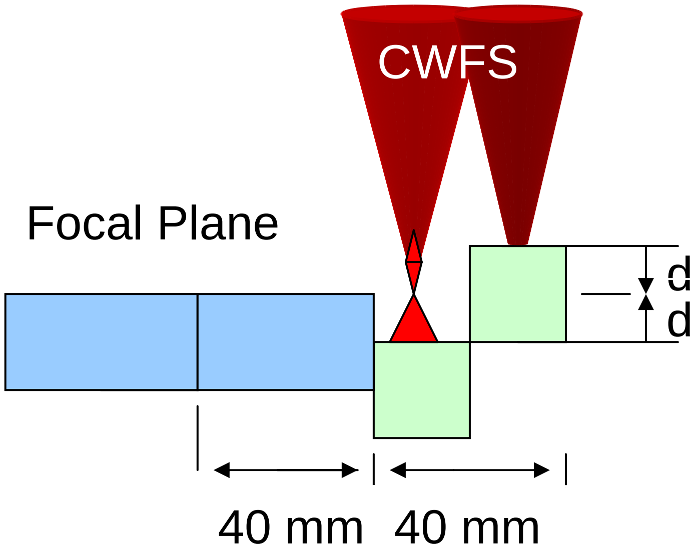


Tomography geometry

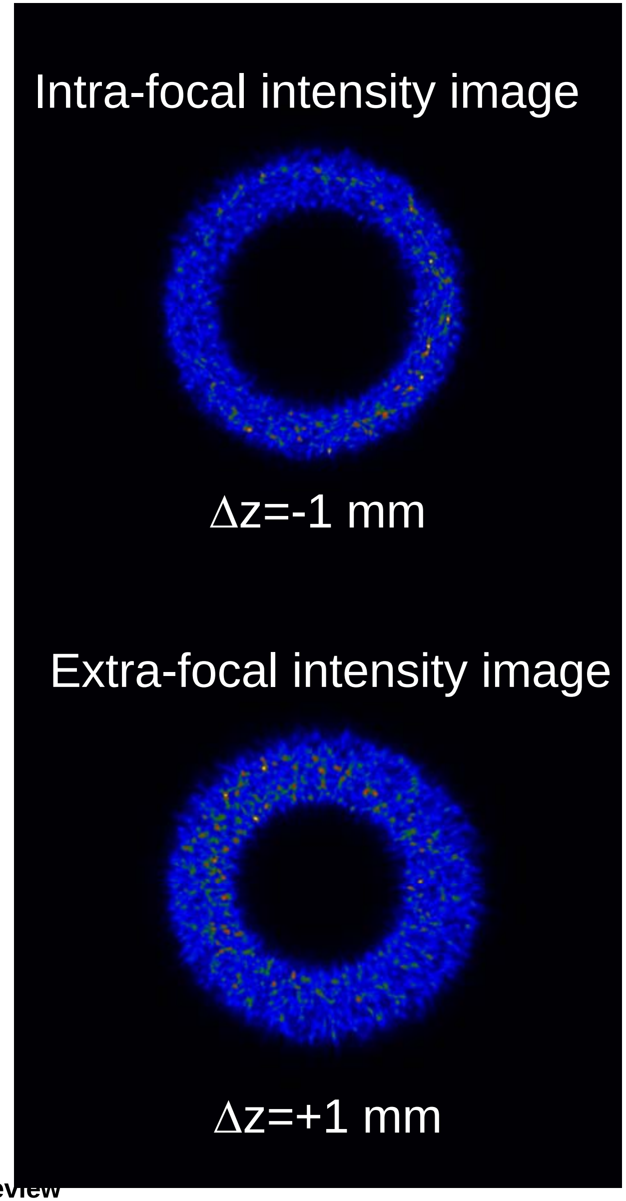
Ref: George N. Lawrence and Weng W. Chow, Opt. Lett. **9**, 267 (1984).
D.W. Phillion, S.S. Olivier, K.L. Baker, L. Seppala, S. Hvisc, SPIE 6272 627213 (2006).
K.L. Baker, Opt. Lett. **31**, 730 (2006).

Curvature wavefront sensor

- **Recording images on each side of focus enables reconstruction of wavefront aberrations by solving the transport of intensity equation**
- **Wave optics modeling has been performed to analyze images from curvature sensors**
  - **Includes effects of atmospheric turbulence and noise**

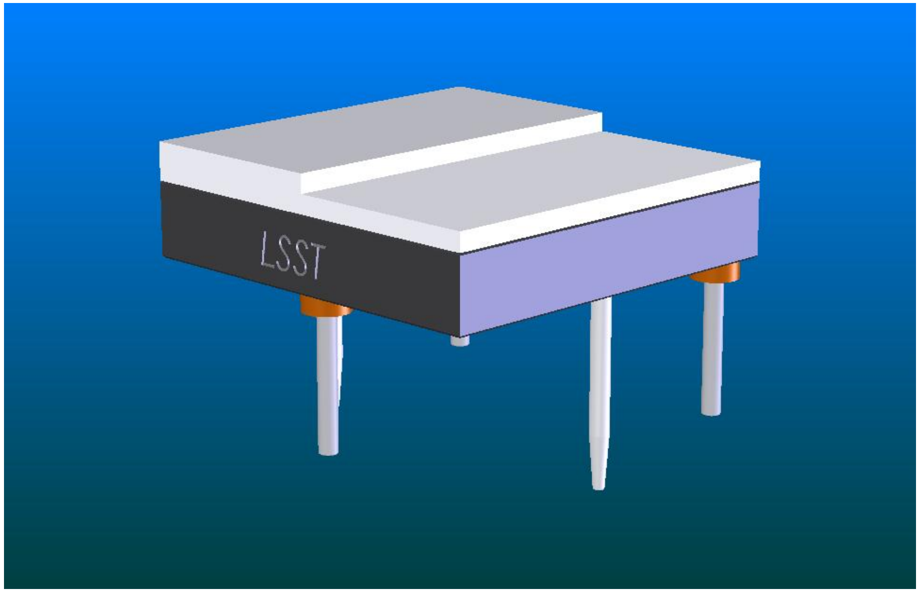


Curvature wavefront sensor geometry



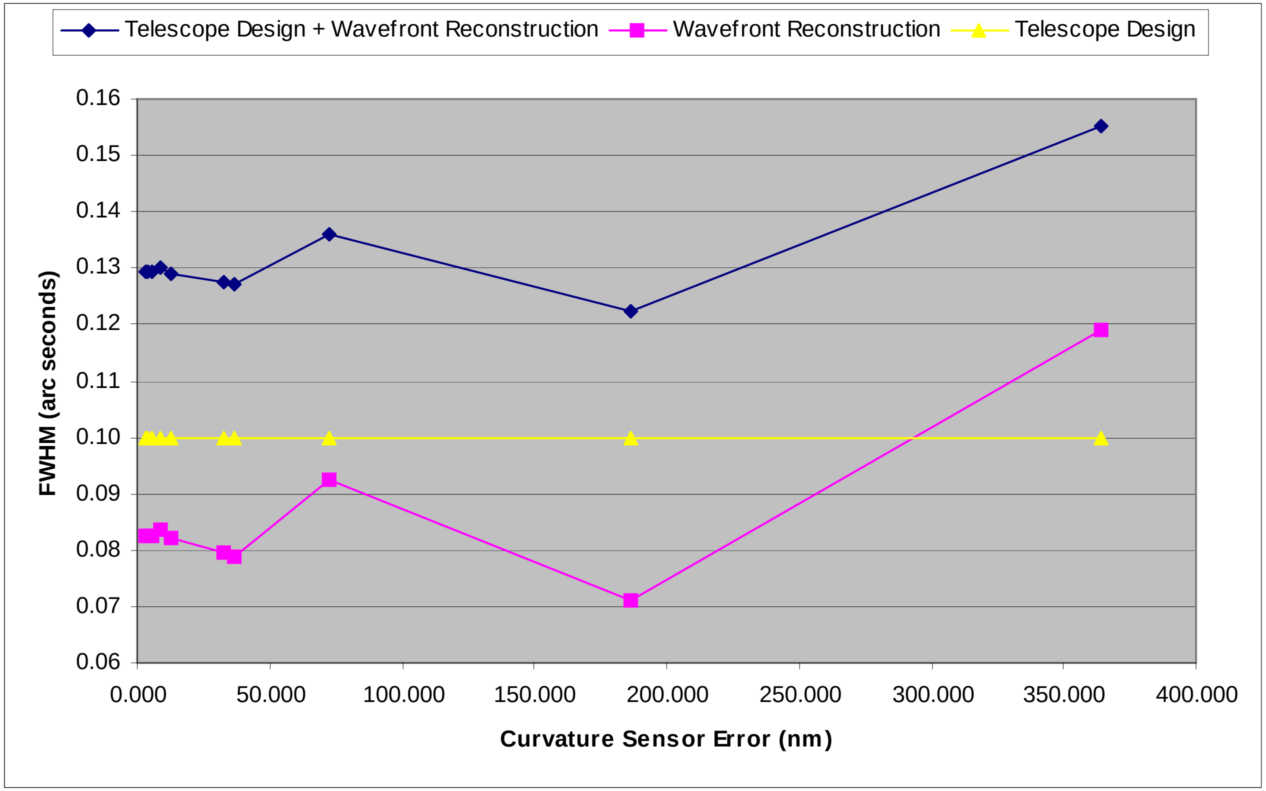
Wavefront Sensors Assemblies: Design Details

- **Curvature sensor design images two different fields at two different focal positions**
- **Design uses the same detector technology as the science focal plane array, but with half the size in one dimension to enable shifting focal position between two halves of sensor**
- **Pinout can be identical to normal science sensors (multilayer AlN substrate)**
- **Looks identical to Timing/Control Module & CCS**



Wavefront Sensors: Required Accuracy

- Wavefront sensor errors are propagated through the tomographic wavefront reconstruction resulting in errors in the controlled shapes of the telescope mirrors
- An image FWHM error budget of < 0.10 arc second is achieved for this wavefront sensor configuration with < 200 nm wavefront sensor errors and 200 nm residual atmospheric aberration for 15 second exposure

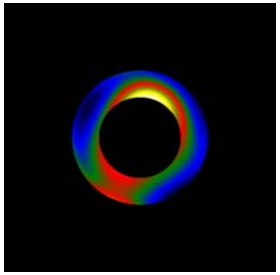


- Fundamental Issue: Are there enough field stars of the magnitudes necessary to provide the required wavefront accuracy in each of the 4 sensors for each pointing?

Curvature WFS images and phase vs. stellar magnitude

- **Wavefront sensor images of dim stars are sky background limited**

Applied phase

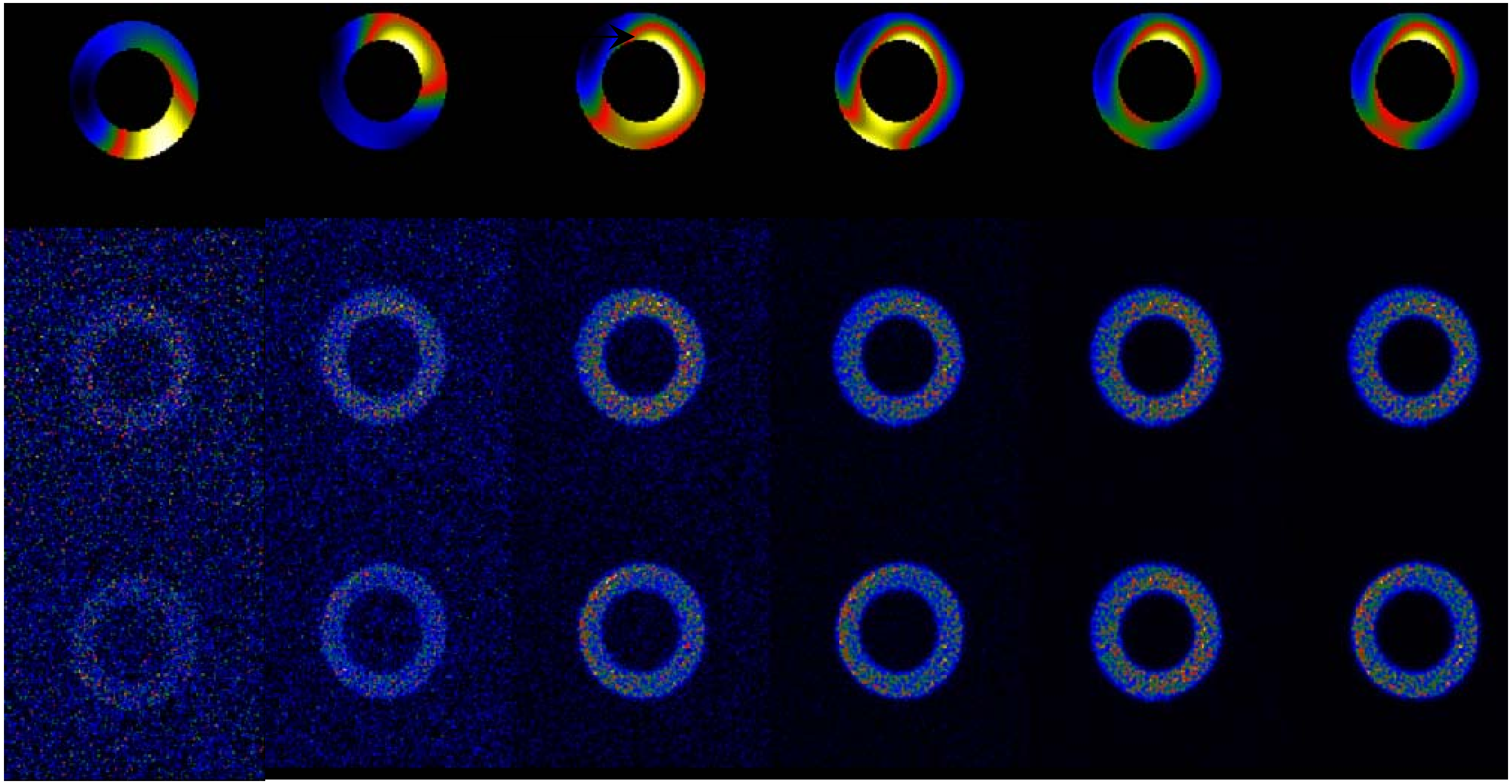


Stellar Magnitude (i band) 19 18 17 16 15 14

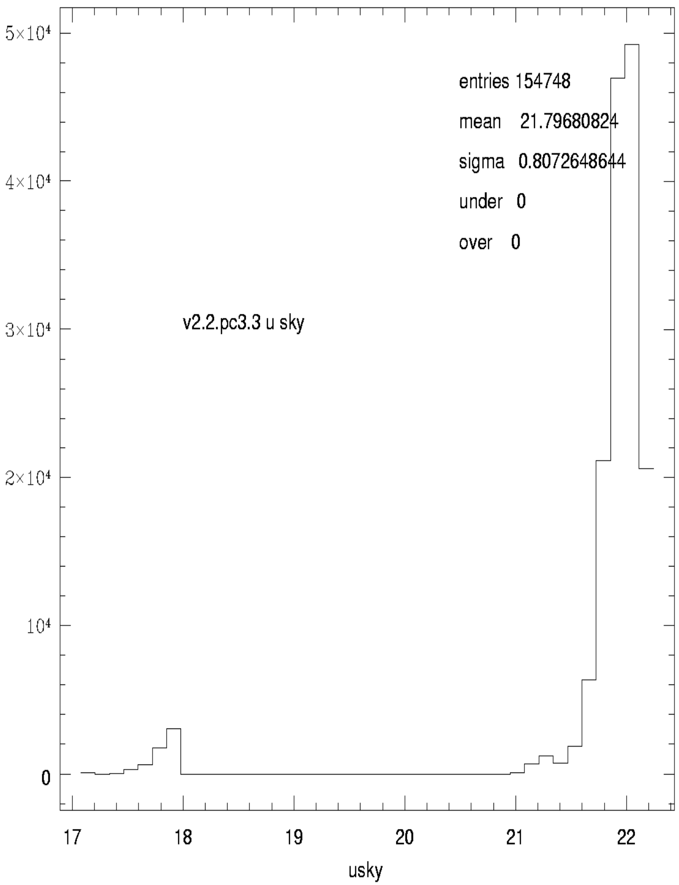
Reconstructed phase

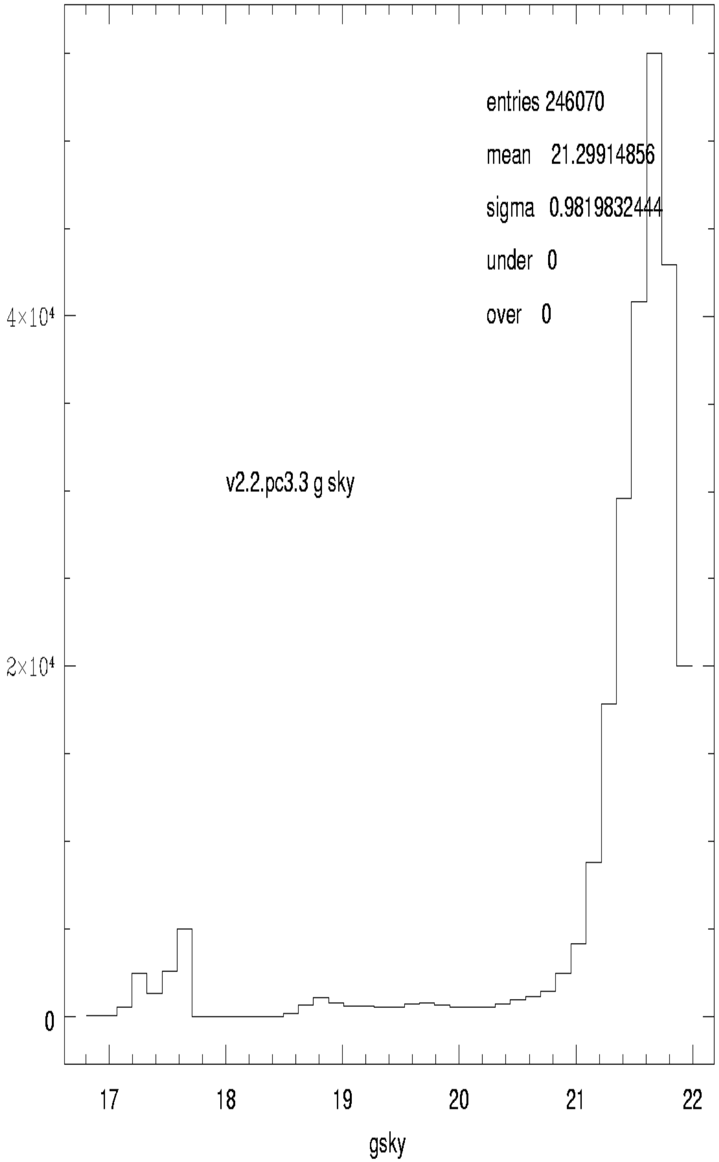
Intra focus CCD Image

Extra focus CCD Image

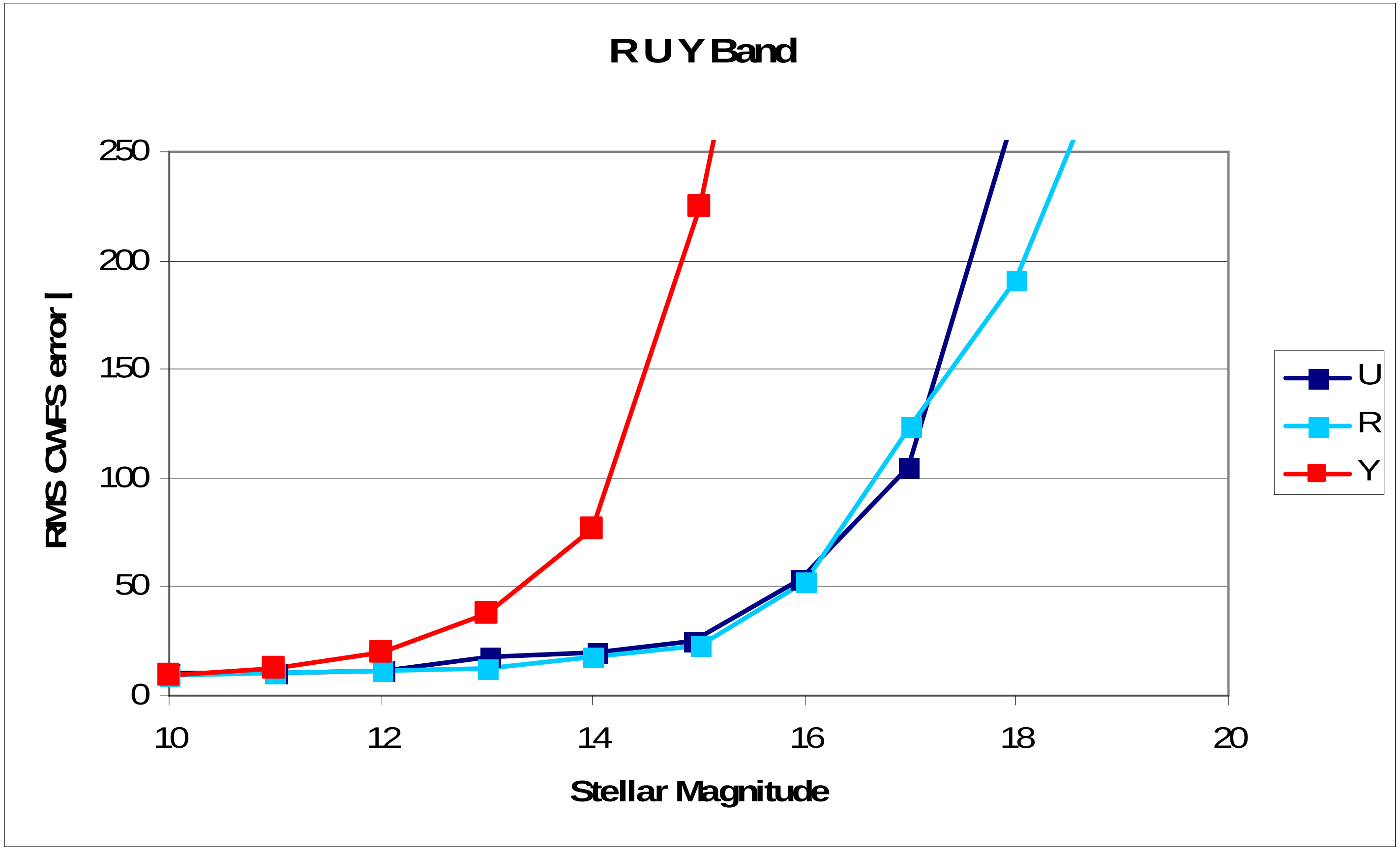


Histograms of sky brightness in LSST survey

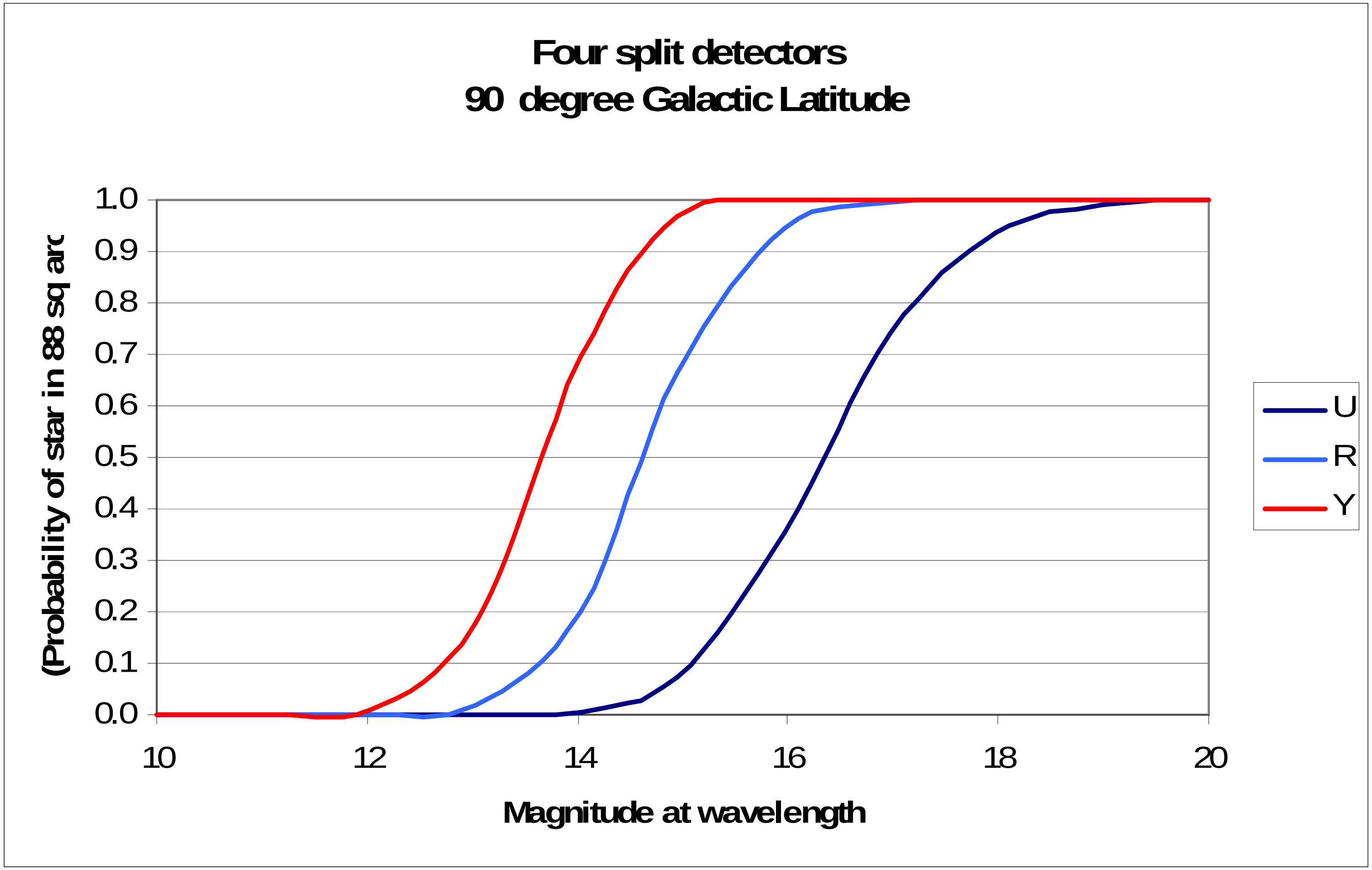




RMS CWFS error vs. Stellar Mag.

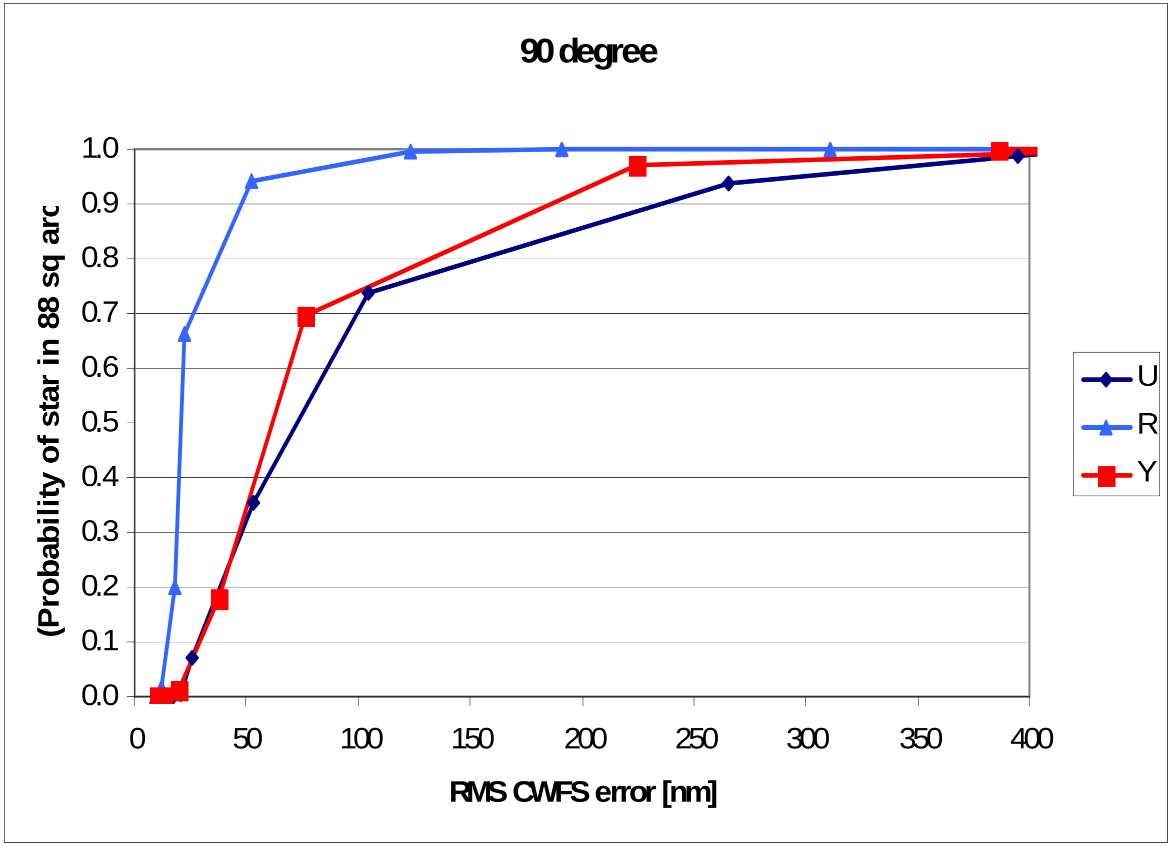


Probability of finding stars as a function of magnitude



Probability of finding stars as a function of CWFS error

- There are enough field stars of the magnitudes necessary to provide the required wavefront accuracy in each of the 4 sensors for each field in g, r, i, z
- At high galactic latitudes ~5% of fields in y and ~15% of fields in u will have degraded accuracy due to the absence of bright field stars
- If wavefront sensor errors are too large, the control system can delay mirror adjustments until the next pointing with little degradation in optical performance

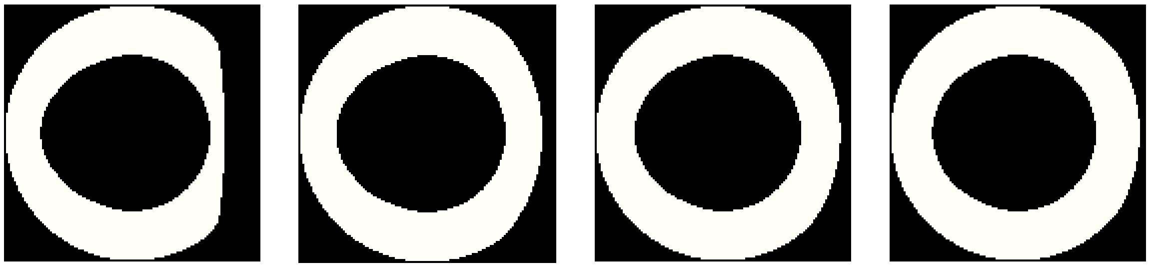


Wavefront Sensors Assembly: Issues

- **Wavefront Sensor Baseline Validation**
  - **Is there a curvature sensing algorithm that works for a split detector at the edge of the LSST field ?**
    - Challenges include variable vignetting, registration between extra-focal images, variable atmospheric dispersion
    - Yes, the vignetting can be corrected, and the correct registration determined, atmospheric dispersion to an accuracy related to the uncertainty in the stellar spectral energy distribution
    - Pistoning the detector between exposures also investigated
      - current analyses indicate this approach, which introduces mechanical complexity, not necessary to achieve the required performance
  - **What is the required axial shift for the extra-focal images?**
    - Atmosphere – bigger shifts
    - Detector noise, crowding – smaller shifts
    - 1 mm meets requirements
    - Crowding analysis shows isolated stars can be found
  - **What are the requirements on flatness and positioning of the wavefront sensor detectors?**
    - Flatness spec nominally similar to science arrays but
      - additional analysis ongoing to investigate possible relaxation of spec
      - detectors likely to have characteristics similar to science arrays
    - Positioning of detectors relative to focal plane relatively insensitive
      - offsets of up to ~100 microns (1/10 of nominal 1 mm offset) can be calibrated on the sky

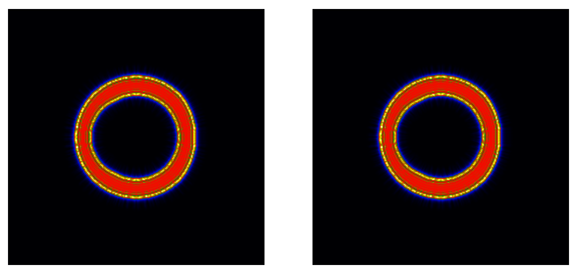
Analysis of variable vignetting

Θ=1.78 degrees Outside corner	Θ=1.75 degrees Max field angle	Θ=1.62 degrees CWFS area center	Θ=1.45 degrees Inside corner



Pupil vignetting

- **Vignetting is variable throughout wavefront sensor field**

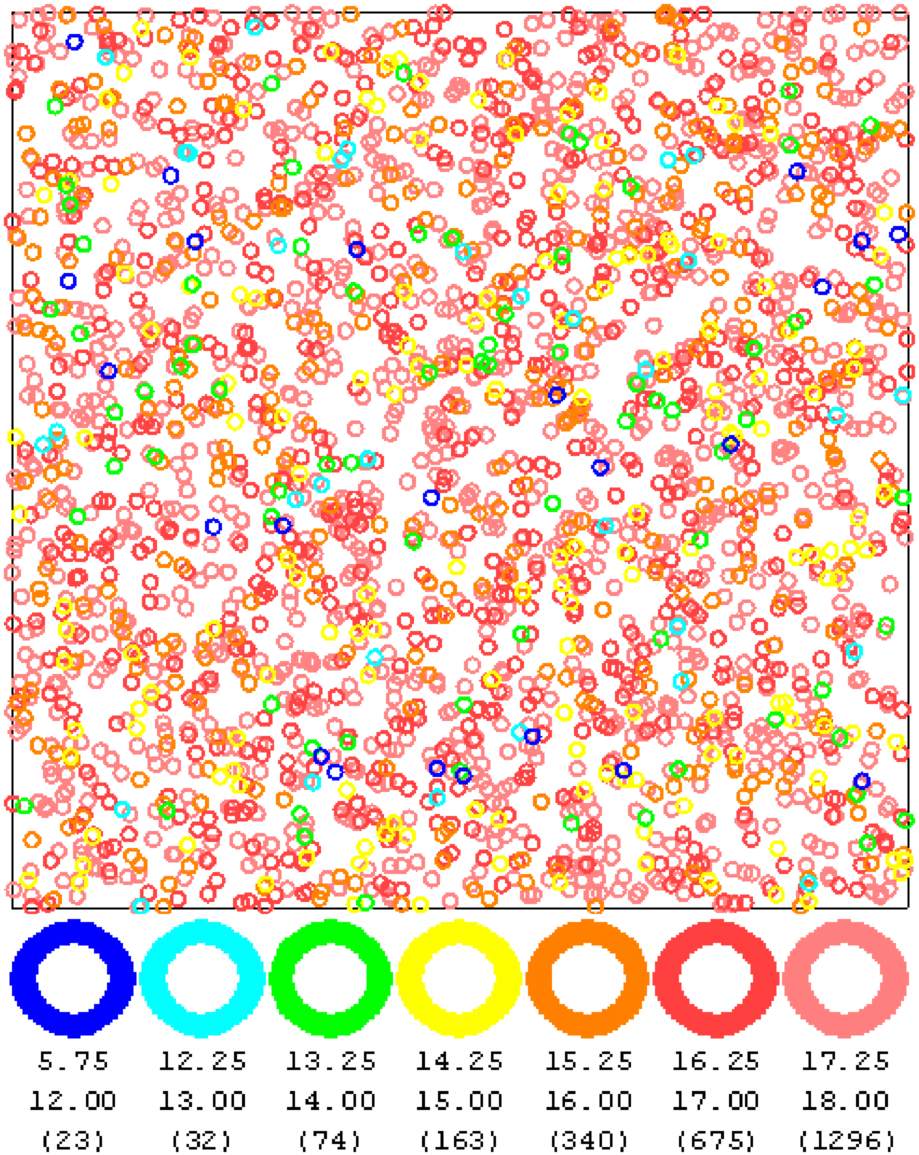


Θ=1.62 degrees CWFS area center	Θ=1.45 degrees Inside corner

Wavefront sensor images including vignetting

- **Analysis demonstrates that wavefront sensor images of stars with different vignetting can be successfully combined to produce accurate measurements**

Analysis of crowded fields



- Typical star field with Δz=1 mm defocus in Y band at galactic equator
- ~10 stars with magnitude y<15 are isolated from all stars with magnitude y<18
- Analysis demonstrates that even the most crowded fields still have usable stars for wavefront sensing
  - No need for more complicated deconvolution algorithms

Guiders

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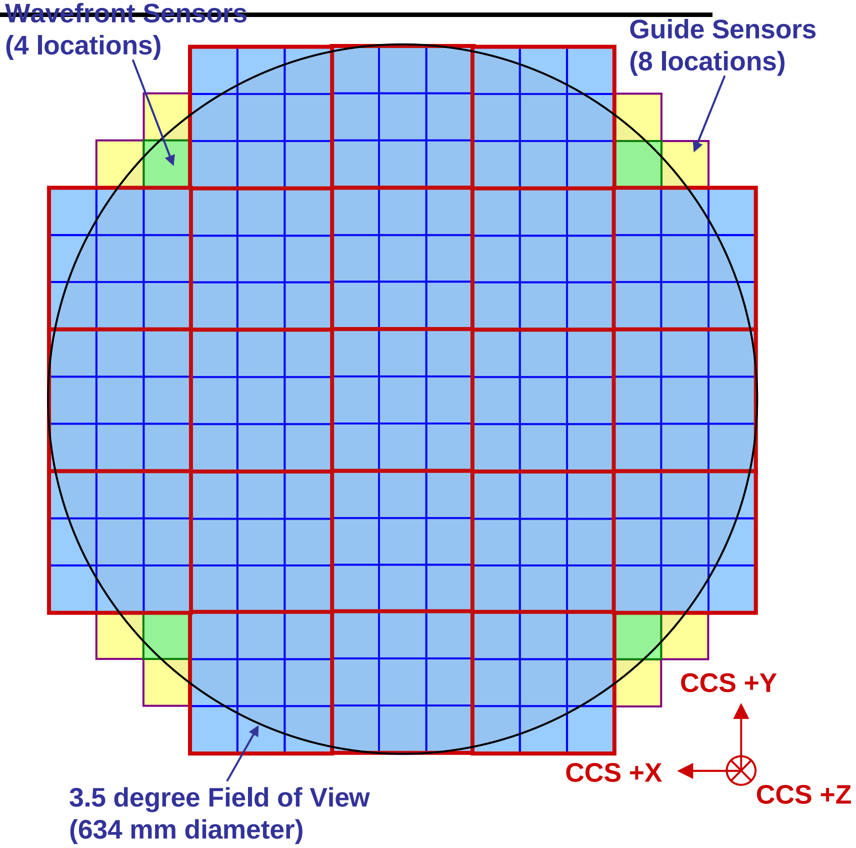
Guide Sensor Assemblies: Reference Design

- Eight guide sensors are located in the corners of the focal plane
  - Guide sensors in each corner raft occupy an area equivalent to 2 science detectors.
- Baseline guide sensors are CMOS detectors
  - The Hybrid Visible Silicon H4RG is a 4K×4K optical imager produced by Teledyne Scientic and Imaging which has recently been tested on the sky at Kitt Peak
  - CCD detectors are still an option to be evaluated

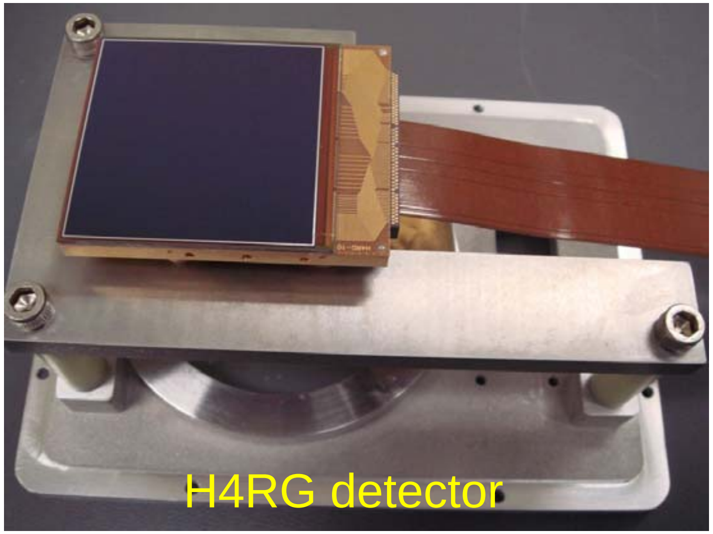


Guider Requirements

Requirement	Definition	Value	Units	Rationale
Centroid noise	error between computed centroid location and true location of star	23.5	mas FWHM	allocation from higher level budget
Update frequency	frequency of centroid updates	10	Hz	loop must converge faster than LSST exposure time
Wavelength range	range of wavelengths for guider requirements	All		SRD
Sky coverage	range of points for guider requirements	All		SRD
Latency	delay between average time of photon arrival in guide image and when centroid is delivered	60	ms	allocation from higher level budget
Number of guide groups	number of independent guide locations	4		At least 2 stars needed to solve for rotation; 4 stars needed to reduce uncorrelated atmospheric jitter to acceptable level
Acquisition delay	time between shutter open and first centroid	100	ms	

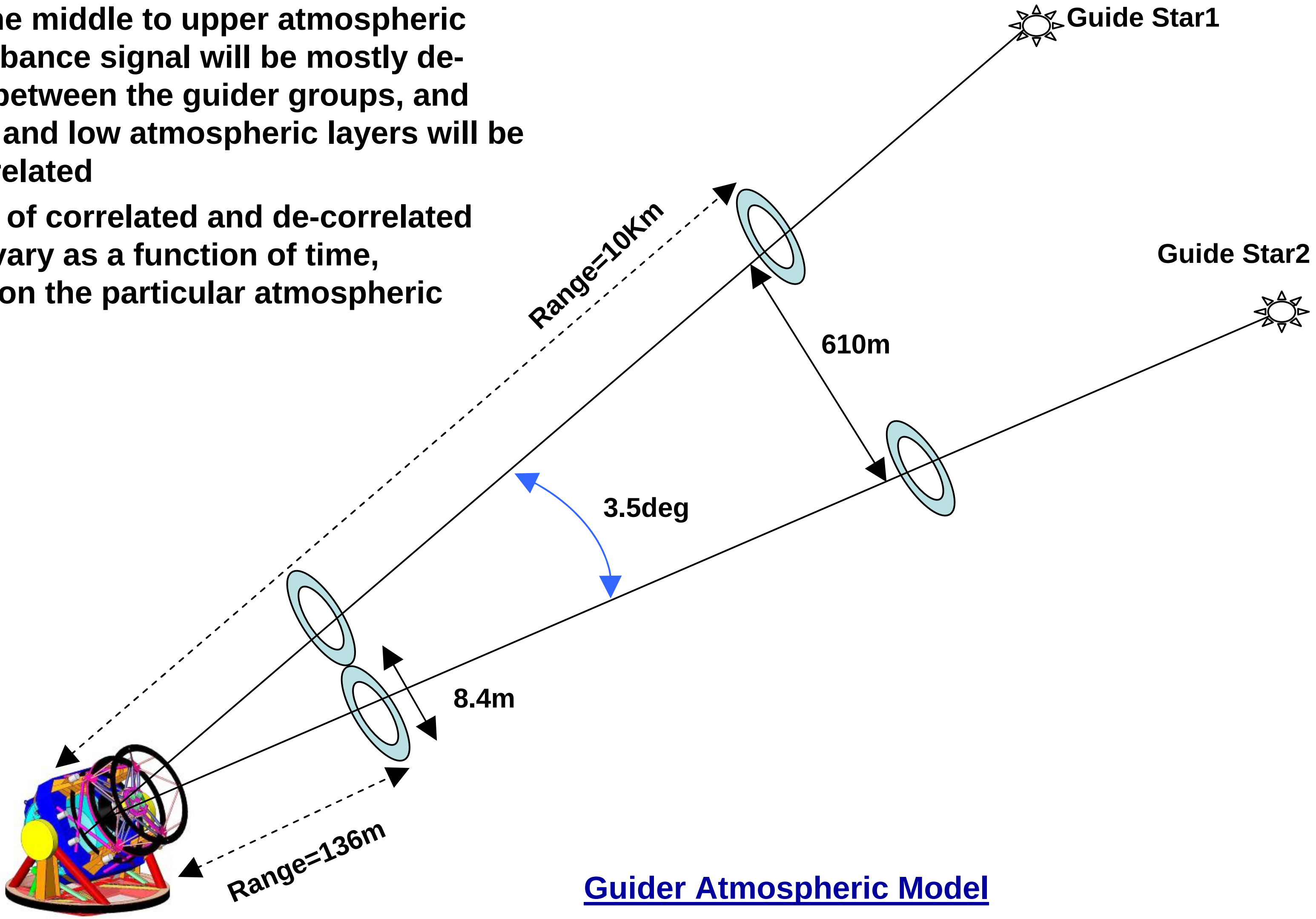
Guide Sensors Assemblies: Design Details

- The baseline guide sensor is a CMOS detector
  - The Teledyne HiViSi H4RG CMOS detector has been tested extensively to evaluate its performance
  - Results from these tests are promising but more development is needed to meet requirments
  - CCD alternatives are under consideration
- A guider processor should receive the signals from the guide sensors via optical fibers
- The command interface to the TCS could be TCP/IP, as latencies are not too critical
- The command interface from the Guider processor to the Telescope Servo should be direct, this is necessary to guarantee a transport delay of less than 10 msec, with no latencies
- The guiders should receive power, communication signals, and cooling via the common Camera/Telescope interfaces



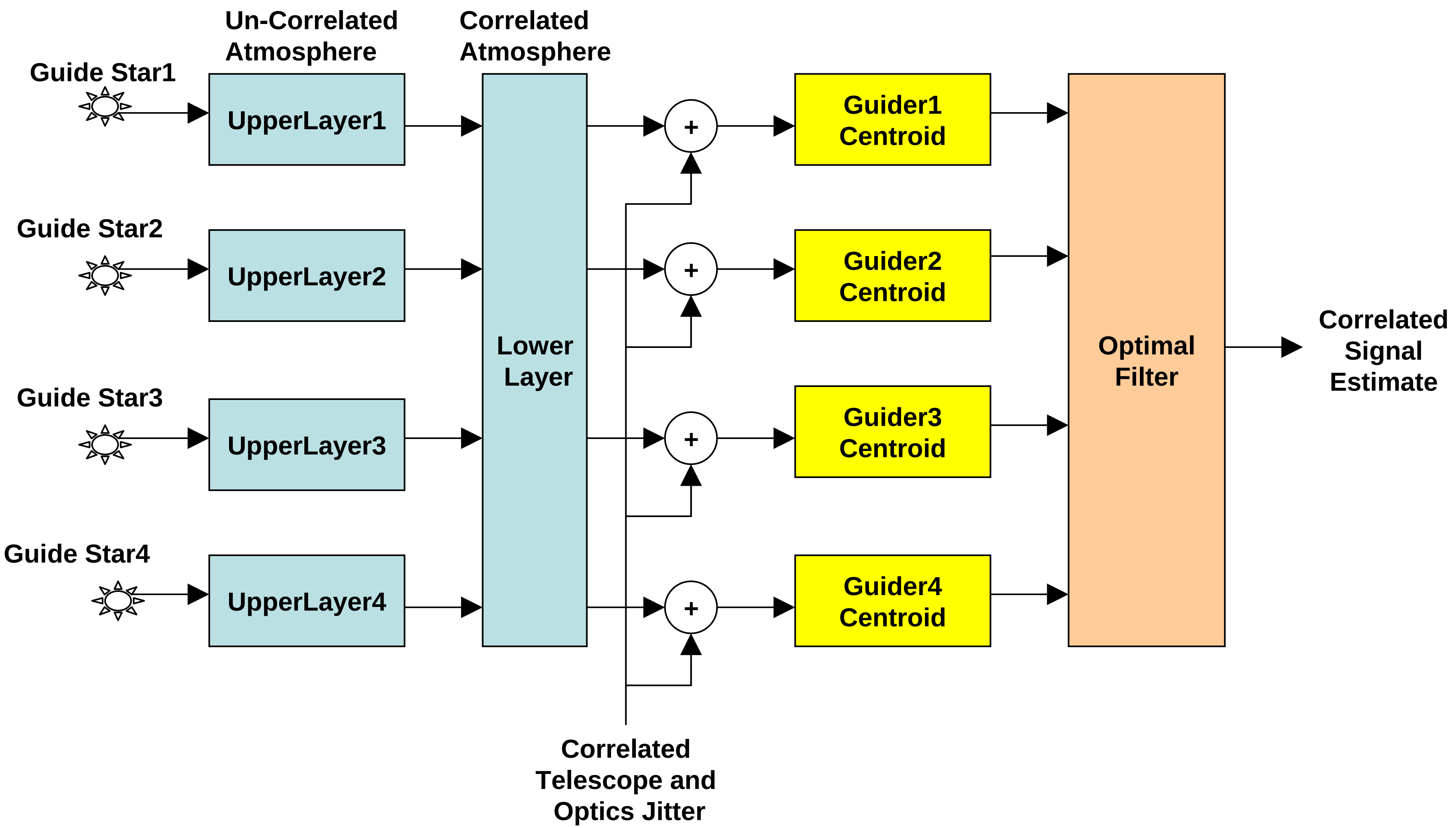
Guider: Atmospheric Model

- The 4 guider groups, will be looking at a different patch of atmosphere above 136m, therefore the middle to upper atmospheric layer disturbance signal will be mostly de-correlated between the guider groups, and the ground and low atmospheric layers will be mostly correlated
- The degree of correlated and de-correlated signal will vary as a function of time, depending on the particular atmospheric conditions



Guider Atmospheric Model

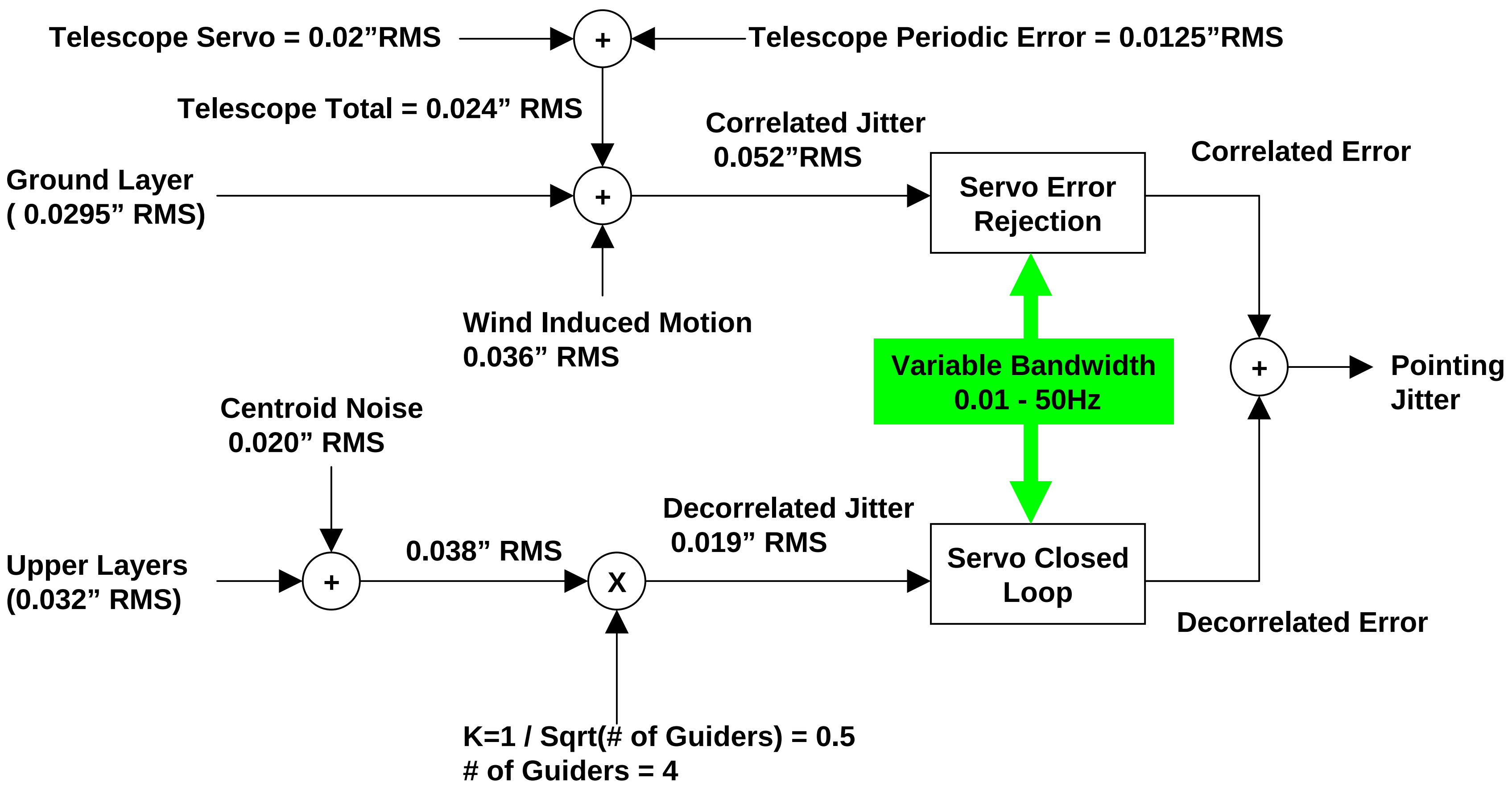
Guider: Signal Model



Guider Signal Block Diagram

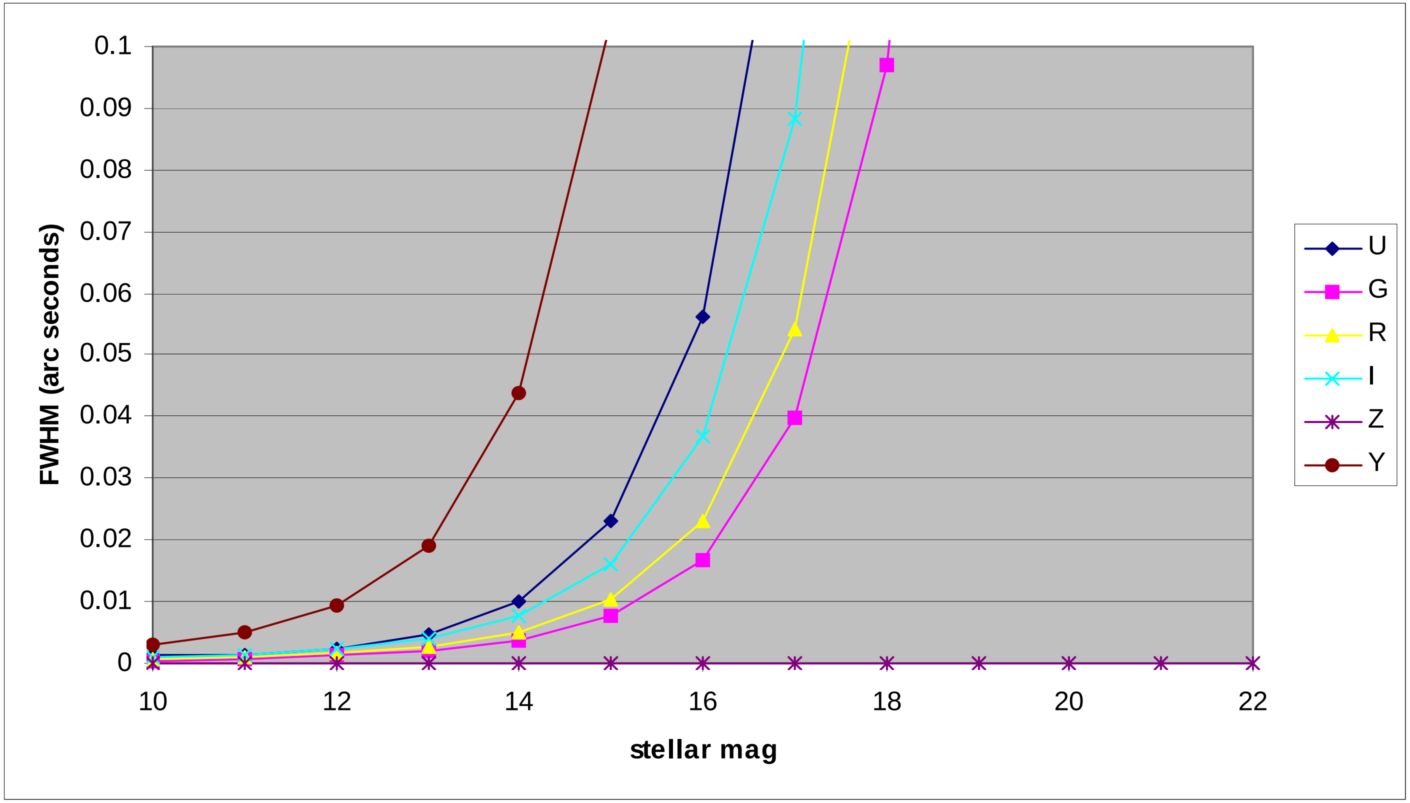
LSST Nominal Guider Signal Budget

Seeing = 0.62"FWHM at Zenith (50%) ,Outer Scale = 23.4m(50%)
Air Mass = 1.243 (50% From Cadence Simulator)



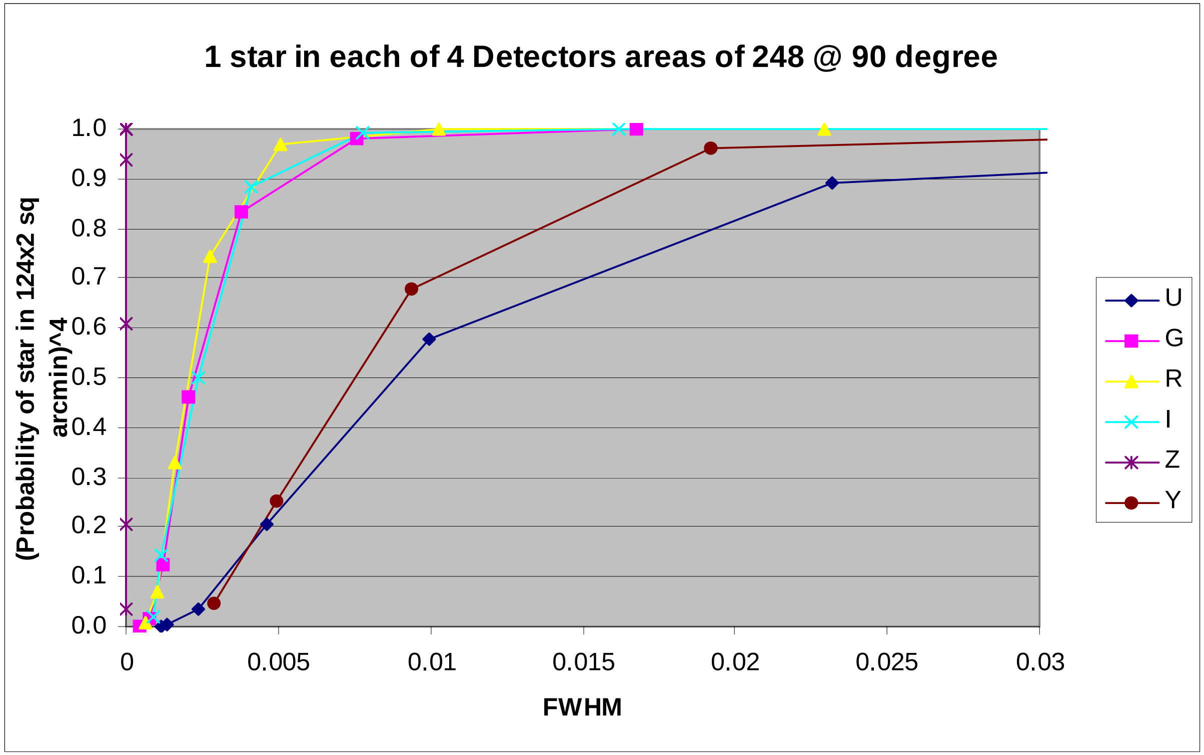
Guide Sensor Assembly: requirements

- **Centroid noise error budget allocation < 0.02 arc second FWHM is met for stars ranging from magnitude 13 (y) to 16 (g) for a guide sensor with 20 electrons read noise using a 10x10 pixel window around the star**
  - **better performance can be obtained using a matched filter or correlation algorithm.**



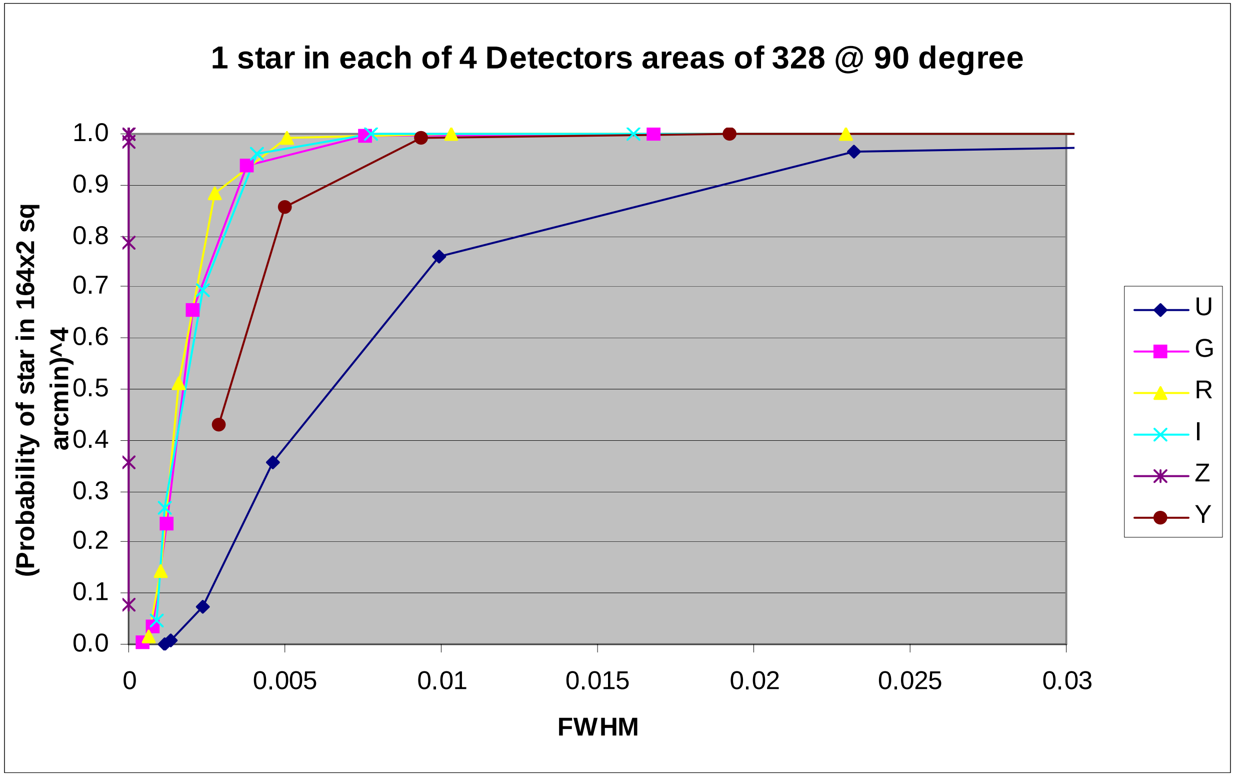
Guide Sensor Assembly: Analysis

- Fundamental Issue: Are there enough field stars of the magnitudes necessary to provide the required centroid accuracy in each of the 4 corners for each pointing?
- There are enough field stars of the magnitudes necessary to provide the required centroid accuracy in each of the 4 sensors for each field in g, r, i, z
- At high galactic latitudes ~4% of fields in y and ~20% of fields in u will have degraded accuracy due to the absence of bright field stars
- The effect of this degradation on overall image quality may be acceptable for these fields



Guide Sensor Assembly: Analysis

- Increasing the FOV by slightly enlarging L3 and the filters, provides improved probabilities of finding a star in each corner position with the required brightness.
- With this modification, there are enough field stars to provide the required centroid accuracy in each of the 4 sensors for each field in g, r, i, z, y
- At high galactic latitudes ~10% of fields in u will have degraded accuracy due to the absence of bright field stars



Guide Sensor Assembly: Issues

- Guide Sensor readout time is specified in the baseline design at <10 ms.
  - For a 4kx4k device with 16 readout amplifiers, this implies pixel rates for each amplifier of 100 Mpixels/second in order to read the entire device – probably too fast to get reasonable read noise performance.
  - If the position of the guide star(s) is known, a CMOS device can read out a sub-area around the star(s), reducing the required pixel rate to a manageable level.
  - If a CCD is employed, probably need to keep pixel rate to ~10 Mpixels/second per amplifier, which implies a readout time more like 100 ms.
    - Need to evaluate effect of increasing latency on guider system performance