Large Synoptic Survey Telescope

A Prototype Wavefront Sensing Pipeline for the LSST

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The Large Synoptic Survey Telescope (LSST) is a planned 8.4 meter fast, wide-field telescope. Its ~10 square-degree field of view will allow the night sky to be entirely surveyed every four nights. The large structure of the telescope, combined with its fast operating scheme, will require an automated active optics system that can correct for optical distortions to produce sharp, optimal images. The active optics system (AOS) employs wavefront curvature sensing (WCS) located at the four corners of the inscribed square within the 3.5 degree field-of-view. The measured wavefront errors are used to determine the displacements and surface corrections in the AOS. To save operating time, we had to minimize human interaction in the WCS process by making the WCS software as automated as possible. We designed and coded this automated WCS software in a Matlab graphical user interface (GUI), which takes in input data (intra/extra-focal images), automatically cleans the data (bias-subtraction, trimming, and removing bad columns), and automatically converts the image data into data that can be passed to the WCS code. The WCS code uses a Fourier based algorithm to solve the intensity transport equation and estimate the system wavefront errors. These errors can then be corrected for by adjusting the physical components of the telescope's optical system.

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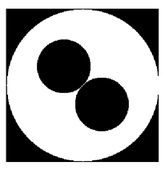
Optical System Definition

Before running the pipeline the basic physical parameters of the optical system need to be defined in consistent units. These include:

- Reference aperture diameter
- Effective focal length
- Offset of the intra/extra focal image planes
- Aperture geometry, including vignetting and obscurations
- Sensor pixel size and sub-image array size

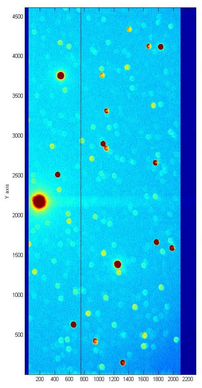


The aperture geometry is specified by an mask list. Each mask list element is a group of 4 numbers specifying the center of a circle (X,Y), a scaling factor relative to the reference aperture, and a Boolean operator to indicate whether the circle is inclusive (1) or exclusive (0). For example, the figure above is created from the following mask list:

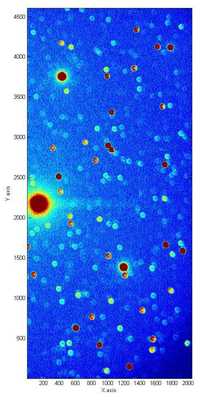
M=[0 0 1 1; -0.25 0.25 0.25*sqrt(2) 0; 0.25 -0.25 0.25*sqrt(2) 0]

Image Preprocessing

Raw FITS image



Processed image



The image processing module provides for basic reduction for the removal of the instrumental signature, including: bias over scan subtraction, trimming, image-bias subtraction, flat-fielding, and removal of bad columns. The processed image contains out-of-focus, donut-shaped sources, which are then extracted for the wavefront analysis. The FITS image format is used throughout the processing and analysis steps.

Curvature Wavefront Estimation

The Theory:

$$\frac{\partial I}{\partial z} = -(\nabla I \cdot \nabla W + I\nabla^2 W) \qquad 1$$

$$\nabla I = -I_0 \hat{n} \delta_c \qquad 2$$

$$-\frac{1}{I_0}\frac{\partial I}{\partial z} = \nabla^2 W + \delta(edge)\frac{\partial W}{\partial \vec{n}} \qquad 3$$

We begin with the Irradiance transport equation (1) and add Neumann boundary conditions (2). The longitudinal derivative of the Irradiance of an optical system can be expressed as (3), where W is the wavefront error in units of length, not phase, and δ_c is a ring delta function around the edge. The longitudinal derivative normalized by I_0 can be approximated as:

$$\frac{1}{I_0}\frac{\partial I}{\partial z} \approx \frac{I_1 - I_2}{I_0 \cdot 2\Delta z} \approx \frac{1}{\Delta z}\frac{I_1 - I_2}{I_1 + I_2}$$

$$I_1 = I(z - \Delta z)$$

$$I_2 = I(z + \Delta z) \qquad 4$$

$$\Delta z = f(f - l)/l$$

If we constrain $\frac{\partial W_{edge}}{\partial \vec{n}} = 0$, the edge delta function can be absorbed in the Laplacian. An estimate of the Laplacian of the wavefront error can be rewritten as

$$\nabla^2 W \approx -\frac{1}{\Delta z}\frac{I_1 - I_2}{I_1 + I_2} \qquad 5$$

The physical geometry needed for curvature wavefront sensing is shown in the figure (right).

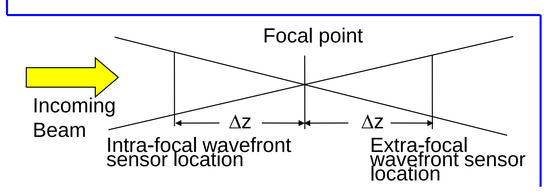
A numerical solution using the Fourier Transform:

Using the Fourier relationship (6), we can solve for W by substituting the right-hand side of equation (5) into the left-hand side of equation (6) to arrive at a wavefront estimate (7) using the inverse Fourier Transform (*IFT*).

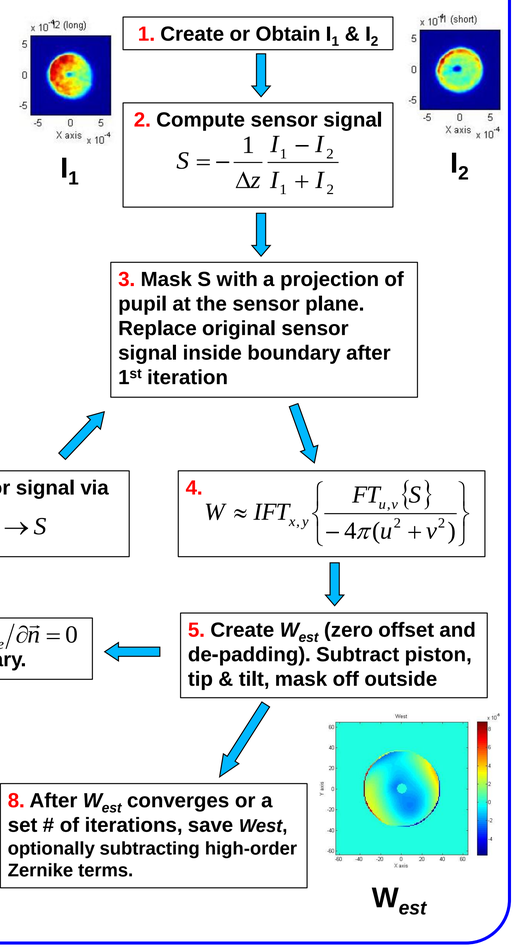
$$FT_{u,v}\{\nabla^2 W(x,y)\} = -4\pi(u^2 + v^2) FT_{u,v}\{W(x,y)\} \qquad 6$$

$$W \approx IFT_{x,y}\left\{\frac{FT_{u,v}\left\{-\frac{1}{\Delta z}\frac{I_1 - I_2}{I_1 + I_2}\right\}}{-4\pi(u^2 + v^2)}\right\} \qquad 7$$

References
[1] E. Ribak, "Experimental limits on curvature sensing", SPIE 3866, 217-220 (1999)
[2] C. Roddier, F. Roddier "Wave-front reconstruction from defocused images and the testing of ground-based optical telescopes", J Opt Soc Am A 10, 2277-87 (1993)
[3] J. Gaskill, Linear Systems, Fourier Transforms, and Optics, Wiley, 1978.

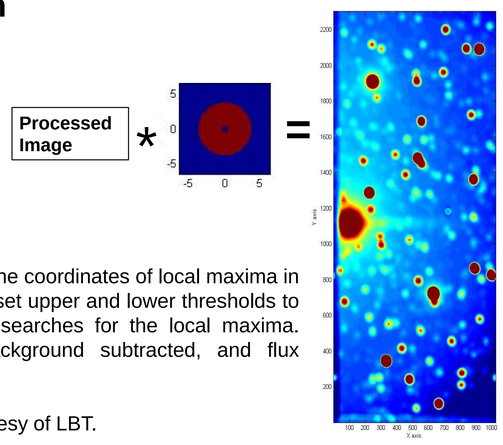


The algorithm:



Source location/extraction

Sources are identified by cross-correlating the original processed image with a template of the out of focus image. The template is derived from the physical description of the optical system. The resulting image has single valued peaks that correspond to the centroids of the out of focus "donut" images.



A peak finding algorithm is used to identify the coordinates of local maxima in the cross-correlation image. The user can set upper and lower thresholds to limit the range over which the algorithm searches for the local maxima. Individual sub-images are extracted, background subtracted, and flux normalized.

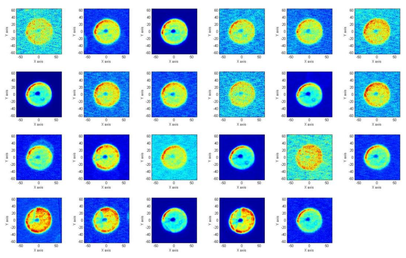
The data used to describe this work is courtesy of LBT.

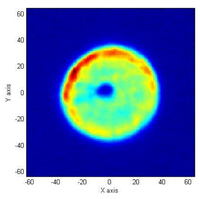
Source Filtering & Selection

The process of source-extraction involves more than just locating sources; not all identified sources can be sent to the WCS code. Some sources are too close to each other, others do not match the shape of the predefined mask well enough, and many others contain too much background noise.

We therefore set up a filtering pipeline that passes all located candidate sources through a series of user-defined tests, keeping only those that pass. These tests check for saturated pixel values and 2nd moment shape analysis for blended or contaminated sources.

The user can then select individual sources that pass these tests (below left) for analysis by the WCS code. Alternatively these can be registered and combined (below right) to improve signal-to-noise and reduce non-instrumental wavefront errors from the atmosphere.





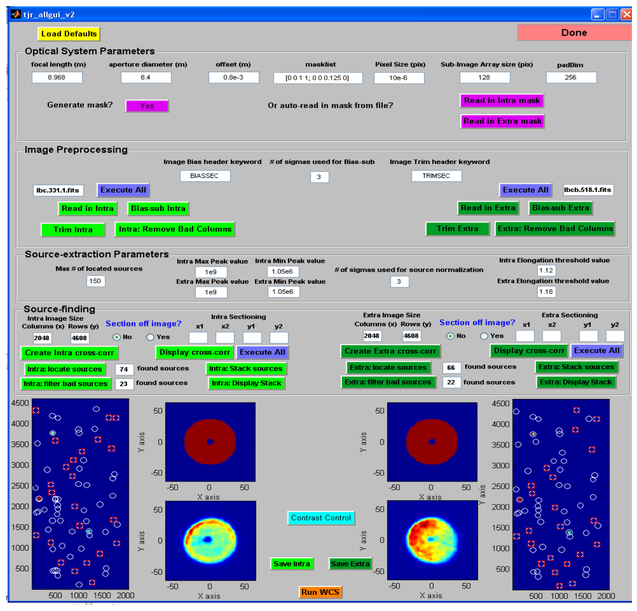
The Graphical User Interface (GUI)

Optical System Definition

Image Processing Controls

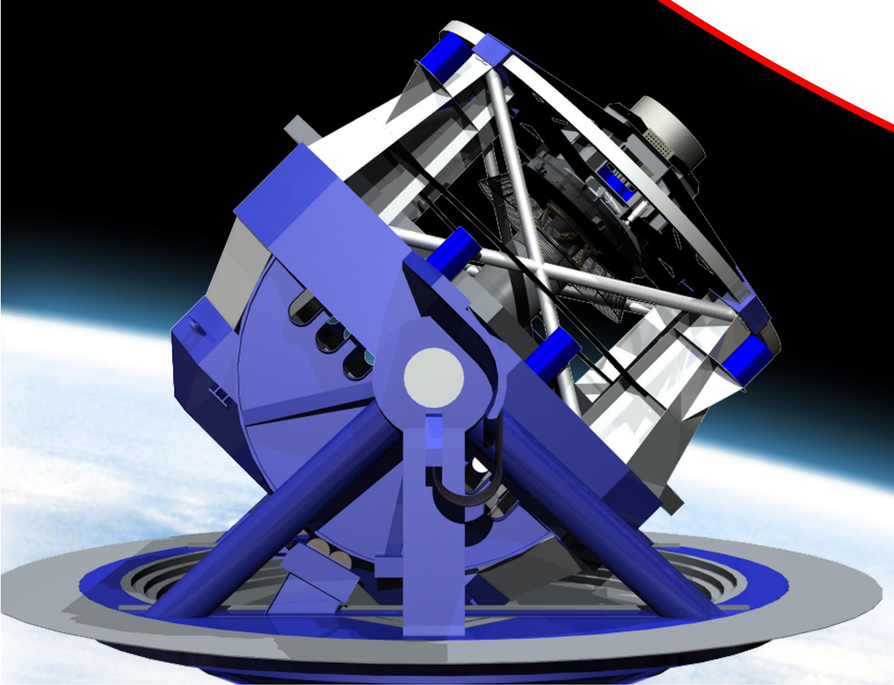
Source Extraction Parameters and Filtering Controls

Image Displays



The GUI controls all tasks. It serves as the pipeline by which the input raw images eventually output valuable information on the telescope's mechanical errors and distortions. Every task within the GUI also functions automatically. The built-in functions also contain user-defined parameters to allow flexible testing and analysis.

This tool is currently being expanded into a fully automated prototype pipeline with a built in optical reconstruction module, and links to Zemax to test the approach as a full Active Optics Control system for LSST.



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