Comparative Wavefront Sensing for a Space Based Segmented Aperture Telescope

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Abstract

The success of phase retrieval on the Hubble Space Telescope (HST) [1][2][3][4][5] led us to consider phase retrieval as a possible method of wavefront sensing for future large space telescopes. Phase retrieval can be used in an active optical control loop as the fine figure sensor by utilizing the science cameras with little or no additional optical hardware but with an increase in either on-board or ground based computer processing. We show some initial results of our hierarchical optical control loop and discuss our on-going study.

Segmented Aperture Space Telescopes

Possible large scale space based astronomical imaging telescopes, such as the Next Generation Space Telescope (NGST) [6][7] will most likely be a large (~8 meter diameter aperture) operating at least over the wavelength band 1.0 to 5.0 microns and required to be diffraction limited ($\lambda/14$). The size and weight constraints for this class of telescope dictate that the primary mirror (PM) be a lightweight multi-segmented mirror. One of the main technological challenges will be to initially phase the segments, to maintain the segment alignment, and, in general, maintain the alignment and figure control of the whole optical train. This can be a quite daunting task in orbit. Thus, we are evaluating a phase retrieval based optical control system and will be comparing it against more classical methods such as interferometry and Shack-Hartmann sensing. We are first building a high fidelity computer model of the entire control loop and studying a multitude of different methods. This will first be done in a pure computing environment, then, a subset of the methods studied will be tested, in a hardware configuration, on the Developmental Cryogenic Active Telescope Testbed (DCATT) [8] and possibly on a technology demonstration flight mission known as Nexus [9]. The Nexus mission will be a segmented aperture telescope adopting the optimal phase retrieval based optical control system tested on DCATT. Figure 1 shows one possible schematic design of an optical control loop for a large segmented aperture telescope. The telescope entrance pupil is imaged onto the deformable mirror (DM) via an off-axis parabola and the telescope's cassegrain focus is relayed to the wavefront sensor (WFS) camera and the fast steering mirror (FSM) camera. The FSM camera is essentially a quad cell motion detector. The control loop for the FSM feeds tip/tilt commands to the FSM to keep the image stationary due to system jitter. The WFS camera collects an image (or set of images) of an unresolved source through a narrowband spectral filter and subsequently passes them through the phase retrieval software system to recover the wavefront errors. These subsequent wavefront errors are used to determine optimal actuator steps which minimizes the prior chosen wavefront quality metric. The actuator commands are sent to the PM/SM (secondary mirror) actuators and to the DM actuators. The choice of control metric determines the image quality. A minimal rms wavefront error gives the sharpest image with regards to the Strehl ratio, but, at the expense of sidelobes in the point spread function (PSF). A maximal encircled energy metric is more optimal for spectroscopy but at the expense of reduced Strehl ratio and more complex control loop algorithm. A wavefront error power spectral density (PSD) metric ensures a smooth roll-off in the wings of the PSF. This may be more optimal for a coronagraph and/or imaging in crowded fields. These different metrics are currently being studied in more detail. It may even be possible to allow the observing astronomer to propose a choice of metric, and subsequently fine tune the telescope for his/her particular observation.

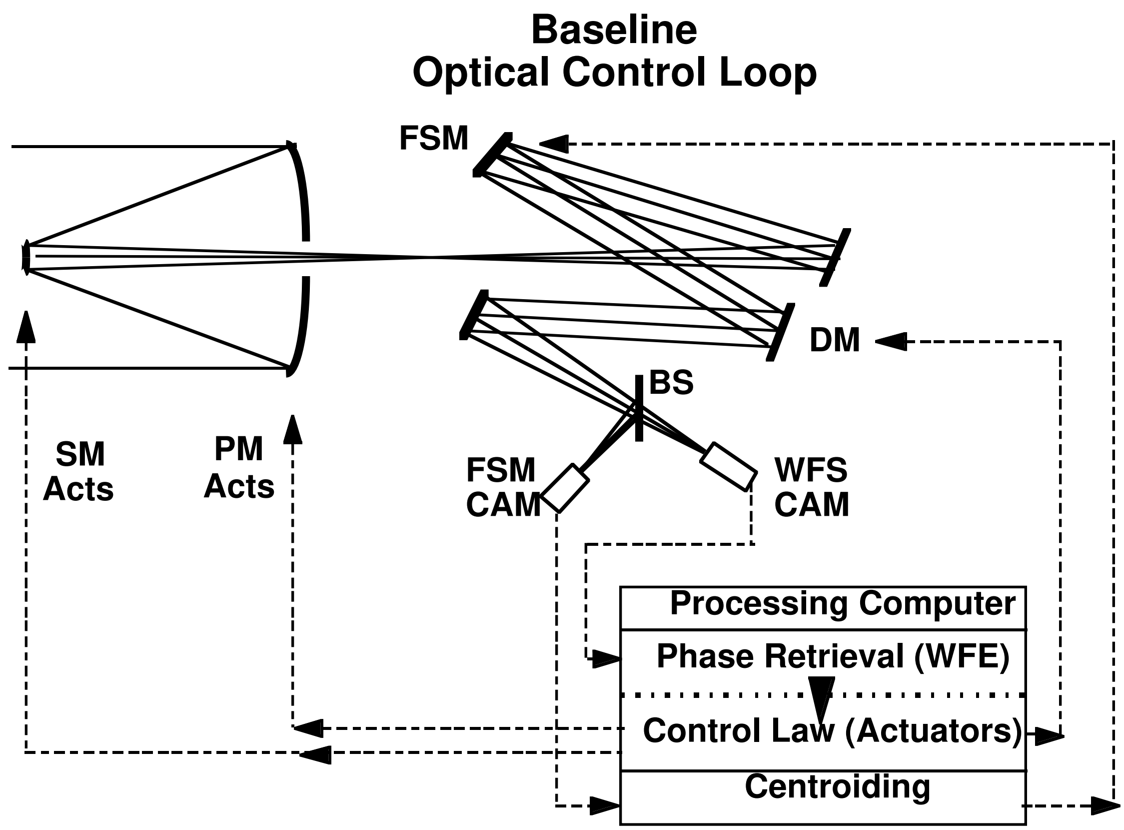

Figure (1)

Conceptual Segmented Aperture On-board Optical Control Loop

Figure (1) is simplified conceptual schematic of one possible phase retrieval based optical control loop. Each of the primary mirror (PM) segments moves in piston/tip/tilt, the secondary mirror (SM) moves as a rigid body in 6 degrees of freedom. The PM is re-imaged onto the deformable mirror (DM) and also onto a fast steering mirror (FSM). The focus of the telescope is relayed through the optical system to both a FSM camera and a WFS camera. The FSM camera is essentially a quad cell detector which centroids the PSF and feed forwards commands to the FSM. The FSM tip/tilts to maintain the position of the PSF on the output camera detector array compensating for system jitter. The WFS camera, essentially the science instrument camera, measures a sequence of images at various foci and/or wavelengths and field positions. The resulting set of images are phase retrieved and actuator commands are generated and fed to the DM, PM and SM. The different foci reduces the images dynamic range accentuating the low level structure containing the higher spatial frequencies. Also, the larger PSFs give more samples across the PSF, thereby making the problem more well-posed and more robust with respect to noise. Using different field positions allows for determination of the field dependence of the aberrations, ensuring unambiguous alignment of the entire optical train. Diversity with regards to wavelength accentuates different wavefront spatial frequencies ensuring a better optical control loop response and also resolves the segment piston ambiguity.

Hierarchical Optical Control Loop

We have currently modeled a generic segmented optical systems, including the telescope baseline design, a generic science camera, wavefront sensing and the optical control loop. This baseline model is currently being used to perform a number of parametric trade studies as well as a number of different phase retrieval based wavefront sensing options and a number of possible different actuator based control loops. We are able to model the operational scenario and to investigate a number of different paths to minimize the as chosen error metric. Figure 2 shows a flowchart of a closed loop simulation. Two, or more, observed PSFs, (in practice we found that 4 worked well) one on each side of focus, are input to the Misell [10] phase retrieval software. The resultant wavefront is recovered, modulo 2π, and input to a phase unwrapping algorithm. This resultant wavefront is fit to the DM actuator influence functions, and the DM surface is moved to compensate for the error to bring the wavefront error down to 0.05 waves rms. The resultant PSF and a "perfect" PSF is shown for comparison; both are logarithmically stretched to enhance low level detail. In this context "perfect" refers to no wavefront error. Note the waffling in the DM corrected wavefront which is due to the underlying actuators.

The control loop hierarchy is such that when the telescope is initially aligned, or, whenever it drifts out of range the Misell phase retrieval approach is used to determine the wavefront error. During science observations a phase diversity approach could be utilized as an in-situ monitor on whatever science image is being integrated. Phase diversity can use extended sources and fields of stars as opposed to an unresolved source that the Misell approach must use. Thus, during the science observation the non-destructive read detectors could be periodically queried and the images passed through phase diversity. However, phase diversity has less accuracy and precision than the Misell approach. Thus once the image quality drifted out of spec, the science observation would be put on hold and new PSFs could be observed and the Misell approach reinitiated, then the science observation continued. Alternatively, if the wavefront error range was held small ($\sim\lambda/4$) we could use the quasi-linear approach [11]. This method relies on a direct solve for the wavefront error and thus no iterative algorithm would be required. It may also be possible as we acquire trend data to use feed-forward approach where the misalignment errors would be predicted based upon past performance and the optics realigned without taking new images. Of course, periodically, new images must be taken to verify performance.

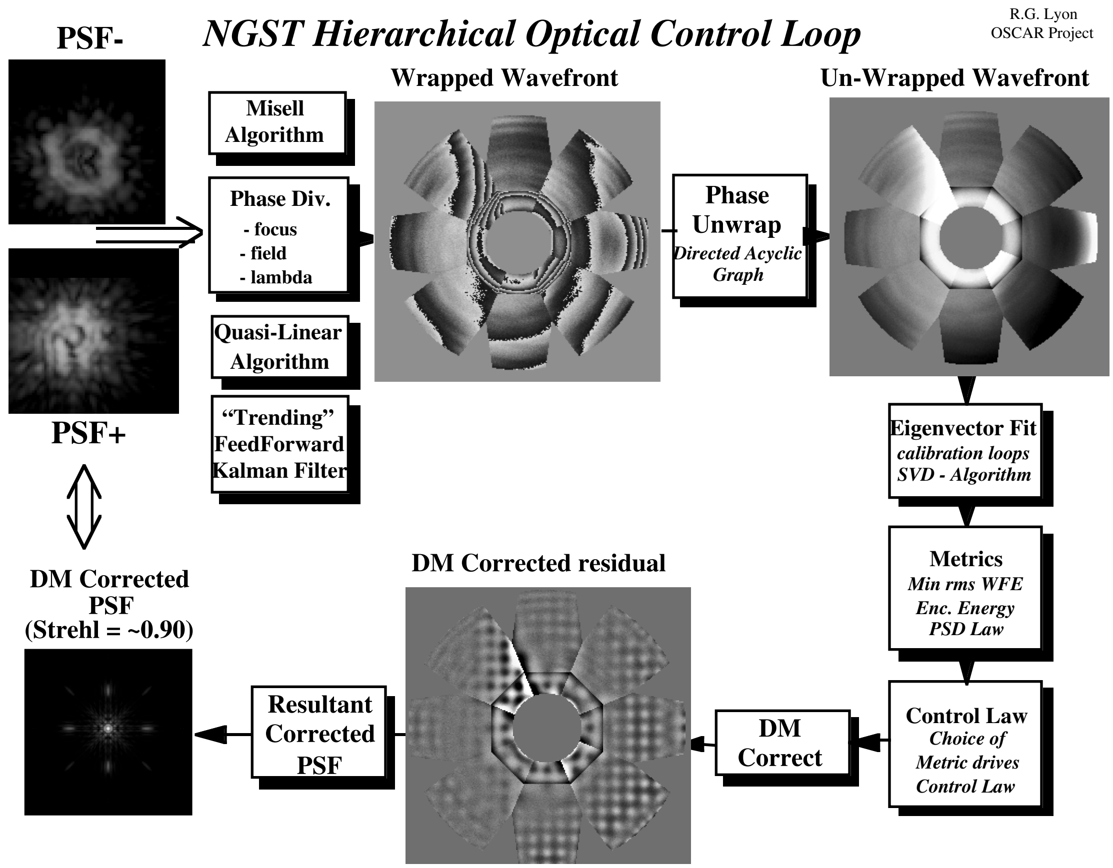

Figure (2)

<u>Segmented Aperture Hierarchical Phase Retrieval Based Optical Control Loop Simulation</u>

Upper left - Two input PSFs, one on each side of focus. These are input to Misell phase retrieval algorithm. Upper middle - Output of phase retrieval is the entire optical trains wavefront error. This is returned modulo 2π unless the wavefront error is less than 1 wave. Upper right - Unwrapped wavefront error. Note that each segment can have it's own errors. This simulation also contains residual polish marks and surface microroughness. Lower right - The un-wrapped wavefront is fit to the actuator influence functions and the DM moved to correct the wavefront. Shown is the residual "quilt" pattern. The DM corrected wavefront is $\lambda/20$ rms WFE. Lower middle - The resultant DM corrected PSF. Note that this is logarithmically stretched to bring up the some the residual background structure. Lower left - The perfect PSF, i.e. with no WFE in the entire system, is shown for comparison. This also has the same logarithmic stretch as the DM corrected PSF.

Optical Systems Modeling and Phase Retrieval

Phase retrieval is essentially a method of finding the wavefront error in an optical system from an ensemble of observed focal plane images. The wavefront error can result from a variety of causes including aberrations due to design residuals, fabrication errors, polish marks, alignment errors, and/or thermal and structural drift. In the phase retrieval technique used here, the inputs are defocused observed images of a narrowband unresolved source such as the images on the left of Figure (2). The output is the wavefront error in the optical systems exit pupil.

The monochromatic point spread function (PSF) is given by:

$$PSF(x,y;W,\lambda) = \left| \frac{1}{\lambda F} \iint A(u,v) e^{ikW(u,v)} e^{i2\pi(\frac{xu}{\lambda F} + \frac{yv}{\lambda F})} du dv \right|^2 \tag{1}$$

where λ is the wavelength; F is the system focal length; W(u,v) is the parameterized wavefront error to be found. A(u,v) is the aperture mask function, 1 where light is passed, 0 otherwise. (u,v) are the pupil plane coordinates and (x,y) are the focal plane coordinates.

The intensity integrated across the spectral response and convolved with the detector spatial response is measured in the focal plane. This is commonly referred to as the point response function (PRF).

$$PRF(x,y;W) = \int PSF(x,y;W,\lambda)\; S(\lambda)\; d\lambda \;\; ** \; rect\left(\frac{x}{\Delta x}\right) rect\left(\frac{y}{\Delta y}\right) \tag{2}$$

Where $S(\lambda)$ is the spectral transmission function, including source spectrum. The detector spatial response function, $\mathrm{rect}(\frac{x}{\Delta x})\,\mathrm{rect}(\frac{y}{\Delta y})$ is assumed wavelength independent across the filter's narrow spectral passband; Δx and Δy are the x and y pixel spatial dimensions, respectively; and the notation "**" represents convolution. Note that the source spectral radiance function is much more slowly varying with respect to wavelength than the filter function and can generall y be assumed contant over the wavelength band of interest.

The measurement model is given by:

$$M(x,y;W,\mathit{flux},A,B,C) = \mathit{flux} * PRF(x,y;W) + A * x + B * y + C + \eta(x,y) \qquad (3)$$

flux, represents the observed PRF's integrated flux; A and B represent gradients in the diffuse background; C is a constant background; $\eta(x,y)$ represents a non-stationary noise component. M is a function of 4 linear parameters (flux, A, B, C) and a non-linear function of the wavefront W(u,v). $\eta(x,y)$ is a random variable and, hence, M is also.

The goal is to find that set of parameters $\{W,\mathit{flux},A,B,C\}$ which maximizes the likelihood of occurrence of observed random variable M. The details of how this is done will not be discussed here but the reader is referred to references [2][3] and the references therein.

An output example of the wavefront error is shown in the upper middle of Figure (2). The recovered phase is returned modulo 2π and must be “unwrapped” to determine the wavefront error, see upper left of Figure (2). The phase retrieval method of wavefront sensing is akin to interferometry but with the advantage that, in principle, no additional hardware is required. The science camera is used to generate the input images and, therefore, inherently has the aberrations associated with the entire optical train. On the other hand, interferometry requires it's own complex, flight qualified, optics which must be calibrated and generally the science camera cannot be used. Hence, this method does not "see" the entire optical train, which requires higher optical tolerances on the instrument. Compared to interferometry, phase retrieval trades hardware for a software solution. However, phase retrieval algorithms are non-linear and, therefore, computer runs are non-deterministic in time. Moreover, phase retrieval requires on the order of Tera-floating point operations and also, requires a validated high fidelity computer model of the entire optical system. Further, solutions can yield potential problems with convergence and phase unwrapping. We are in the process of investigating methods of guaranteeing convergence while minimizing processing time. In addition, our NGST work will investigate a number of different algorithms, and apply them in a Monte-Carlo fashion, to determine the best approach.

Optical Systems Modeling

In order to test the various phase retrieval methods, the Lyon Electro-Optical (LEO) modeling and analysis package has been developed. LEO was used to previously simulate imagery for HST FOC and WF/PC and is currently being used to simulate imagery for the Deployable Cryogenic Active Telescope Testbed (DCATT) and for NGST. LEO currently incorporates the following:

(1) Multiple plane diffraction, Fresnel, Fraunhoffer and rigorous Angular Spectrum.

(2) Segmented apertures and obscurations.

(3) Full aperture Zernike polynomials.

(4) sub-aperture Zernike polynomials (i.e. each segment can have its own set with the center and normalization radius arbitrary).

(5) random power law surfaces with low and high cutoffs, integrated RMS power and also power spectral density slope, this generates speckle in focal plane.

(6) White noise, harmonic and low frequency jitter models.

(7) Deformable mirror influence function models, quantization error and range limits.

(8) Detector modulation transfer function, charge transfer efficiency, pixelization effects, quantization error and dynamic range effects.

(9) Gaussian and Poisson noise models.

(10) System radiometry, specify star color temperature, spectral filter functions, optics transmission and quantum efficiency.

(11) Some extended scene modeling capability as "seen" through the optical system.

(12) Generic coronagrapic capability with assortment of masks and Lyot stops.

LEO output can take the form of any of the following:

(1) Monochromatic or polychromatic Point spread functions.

(2) Point response functions, with detector effects folded in.

(3) Complex pupils functions including amplitude and phase (wavefront error)

(4) Optical transfer function and modulation transfer function, both single wavelength and monochromatic.

(5) Surface to surface raytrace on high density grids e.g., 1024 x 1024 possibly higher.

(6) Output "Scenes" as seen through the entire imaging system.

LEO is entirely written in MPL which is a massively parallel superset of "C". LEO runs extremely fast generally taking less than 1 second to execute for a 15 optical element system and will perform 40 surface to surface diffraction calculations per second. It currently runs on Goddard Space Flight Center's MasPar MP2 computer which is a massively parallel compute engine consisting of 16,384 separate processors with an associated communications grid. LEO can use adjustable array sizes, with the baseline being 512 x 512, thus it can raytrace grids of 512 x 512 rays and perform 512 x 512 FFT's. The simulated PSFs in Figure 2 are outputs from the LEO package.

Inverse Modeling

Currently a number of phase retrieval algorithms are coded and operational. We are in the process of quantitatively studying the accuracy and precision of each of the different algorithms. Some of problems that need to be addressed are the effects of jitter, finite sampling, finite pixel size, finite spectral passband, convergence and stagnation issues, phase unwrapping, and some of the effects due to segmented optics and active optics. We are also studying whether any significant advantage can be gained by performing phase retrieval in an autonomous control loop on-board a spacecraft with minimal or no communications with the ground.

Current Status and Future Work

A number of the studies have been conducted, or are currently in progress, and will be briefly mentioned here. Different sequences of actuation on the PM/SM and DM combination are considered. For example, one trade off study will address whether the PM segments should move only in piston and tip/tilt while the higher order aberrations are corrected by the DM, or, alternatively whether the PM should also correct higher order modes with and without a DM. There are other issues as well. For example would it be better to thermally control the PM and possibly the SM; how can we continuously monitor image quality, what control scenario minimizes the "waffling" introduced due to the DM; how can we fold in trend data to the control loop; what can be gained, from a scientific point of view, by performing the WFS and optical control system autonomously on-board the spacecraft without any operator/analyst in the loop. This latter aspect would reduce the telemetry bandwidth for the periodic alignment process and possibly allow alignment more often to maintain higher image quality throughout mission life. Also due to potentially long thermal settling times, it may be better to actively control the optics during and following a slew as opposed to letting the optics come to equilibrium then correcting them. Also how much better image quality can we obtain by using very high density deformable mirrors (~10,000 to 20,000 actuators) and/or a segmented aperture DM. We have also been modeling coronagraphic options and different methods of wavefront sensing through the coronagraph. It is anticipated that the results of these studies will become available to the general community.

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