CHARACTERIZING THE HUBBLE SPACE TELESCOPE USING RETRIEVAL ALOGORITHMS

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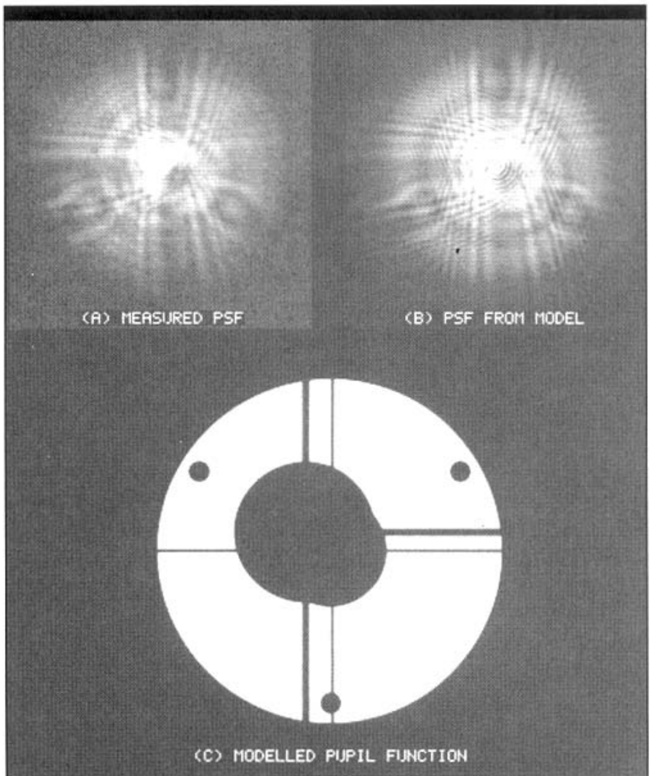
Soon after launch, it was discovered that the Optical Telescope Assembly (OTA) of the Hubble Space Telescope (HST) suffers from a large amount of spherical aberration. An accurate characterization of the aberrations and state of alignment of the HST is important for several reasons: (1) for the design of replacement instruments that will contain correction optics, planned for installation in 1993; (2) for the accurate alignment of the secondary mirror of the telescope; and (3) to analytically compute noise-free point-spread-functions (PSFs) to optimally deblur the images presently being collected by the HST. The analytic PSFs are particularly important for the HST's Wide-Field/Planetary Camera (WF/PC) for which the PSF is highly space-variant.

One approach for determining the aberrations of the HST is phase retrieval. The goal of phase retrieval is to find an aberrated optical wavefront in the entrance pupil, which, when digitally propagated to the CCD detector array plane, produces a PSF [Part (B) of figure] consistent with the measured PSF [a blurred image of a star—Part (A) of figure]. A number of different phase retrieval algorithms were developed by several groups to determine the aberrations.

The phase retrieval algorithms found to be most useful for this problem are those that characterize the aberrations, which are largely smooth, by the coefficients of a low-order polynomial expansion. Typically, up to 11 or 22 terms of modified Zernike polynomials are employed. The coefficients that minimize an error metric, measuring the difference between the PSF computed from the estimated aberrations and the measured PSF, are found by standard nonlinear optimization techniques, such as the conjugate gradient method. We derived an analytic expression that allows the entire gradient of an error metric to be computed with only two wavefront propagations,[1,2] which is much faster than gradient calculations using finite differences.

The optimized polynomial approximation to the phase error is then used as an initial input to the iterative-transform phase retrieval algorithm,[1] which yields a point-by-point phase map showing the micro-roughness of the mirror surfaces. As an alternative, we also derived analytic gradients with respect to the values of a point-by-point phase map.

For the extremely tight tolerances (about ±0.01 microns rms of wavefront error) needed on the estimates of the aberrations, we found it necessary to compute the PSF at the detector by (1) digitally propagating an aberrated wavefront from the entrance pupil (including its obscurations) to the image plane of the OTA, (2) propagating it to the plane of the obscurations of the WF/PC relay telescope, (3) multiplying the wavefront there by a mask representing the WF/PC obscurations [central obscuration and spider support—Part (C) of figure], and (4) finally propagating to the detector plane. Each of these propagations can be performed using a diffraction integral, the parameters of which can be determined by ABCD matrix analysis[3] that requires a single fast Fourier transform (FFT) of moderate size (256 × 256). Both the analytic gradient search and iterative transform algorithms were generalized to allow for both multiple-plane propagation and weighting functions, which can discount the effects of bad



(A) MEASURED PSF (IMAGE OF A STAR FROM THE HST)—NOTE THAT THE TELESCOPE JITTER WASHES OUT THE FINEST FRINGES; (B) PSF COMPUTED FROM ESTIMATED MODEL OF ABERRATIONS (POLYNOMIAL TERMS ONLY) AND PUPIL FUNCTION; (C) ESTIMATED COMPOSITE PUPIL FUNCTION OF THE OTA+WF/PC OF THE HST AS DETERMINED FROM THE ITERATIVE TRANSFORM ALGORITHM.

CCD pixels.[2]

Jitter in the pointing of the telescope during an exposure measuring the PSF is another problem [compare Parts (A) and (B) of figure], and algorithms have been devised that account for the jitter.

For accurate phase retrieval, it is necessary to know the space-variant shift of the WF/PC obscurations relative to the OTA pupil. We determined the shift by reconstructing the magnitude of the wavefront in the exit pupil using the iterative transform algorithm.[1] We found that the shift was different from the design, indicating an unintentional misalignment of the optical axis of the WF/PC relative to the OTA.

An estimate of the spherical aberration of the HST's OTA, after accumulating results of several phase-retrieval groups and allowing for an estimated spherical aberration of -0.023 μm rms in a WF/PC relay telescope, is about -0.27 μm rms of wavefront error. This is equivalent to a primary mirror having a conic constant of -1.0142, as compared with the designed value of -1.0023, making the r^4 term of the mirror surface off by 2.3 μm at the edge.

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OPTICAL NMR

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Optical NMR depends fundamentally on a nonlinear optical process—magnetization by the conjugate product of a circularly polarized laser. It appears to be of widespread interest because it combines laser physics and the physics and chemistry of magnetic resonance, two large contemporary fields. "Optical NMR" is the name given to an experiment in which a circularly polarized laser is used in a contemporary NMR spectrometer to induce extra magnetization and spectral features of analytical interest.

The simple initial "alpha theory" was initiated at the Cornell Theory Center.[1] It catalyzed the first experiment, by the team of Warren S. Warren at Princeton, using a very low intensity argon ion laser of only a few tenths of a watt CW power that is guided into an NMR tube with an optical fiber that maintains the all important circular polarization of the laser. With an extended chiral chromophore, broadening of NMR features has been definitively measured and separated from artifacts such as those due to heating. The results were well received in a conference in the United States.

The broadening is in the hertz range and represents the beginnings of an optical NMR spectrum, whose theoretical basis is being worked out by Evans and co-workers at Zurich, using optical pumping and semi classical (magneto-optic) theories. The ultimate theoretical aim is to present a resolved optical NMR spectrum, using the appropriate selection rules, which turn out to be quite different from conventional NMR. The molecular property responsible for optical NMR has been isolated. It is a magnetic/electric/electric hyperpolarizability, of SI magnitude about ten power minus 45 A m^4 V^{-2}. It is closely related to the tensor that mediates the well known Faraday effect and magnetic circular dichroism, and exists in diamagnetic and paramagnetic atoms and molecules, both chiral and achiral.

The initial alpha theory was valid for paramagnetics only. For a given laser intensity in watts per square meter, the expected broadening in hertz of the NMR line can be estimated. This is expected to be site selective, *i.e.*, different for each NMR line of a complex spectrum, or 2D NMR map, so that optical NMR would give very interesting supplementary experimental information. A resolved optical NMR spectrum would be much richer in detail than a conventional NMR spectrum for the same sample.

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ATMOSPHERIC COMPENSATION USING LASER BEACONS

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Researchers at MIT Lincoln Laboratory and the Air Force Phillips Laboratory have demonstrated real-time correction of turbulence induced atmospheric wavefront distortions using laser beacon adaptive optics.[1,2] These experiments could have a profound impact on the course of astronomy during the next decade. The new generation of 8-10 m telescopes will have impressive light gathering capability, but without atmospheric compensation, their resolving power will be no better than backyard amateur telescopes of a few centimeters diameter. Atmospheric compensation may be accomplished using bright stars but, unfortunately, complete sky coverage is not possible