Degradation of the Adaptive Optics Point-Spread Function due to Non-common-path Flexure: A Simple Laser Metrology Solution

E. E. Bloemhof and R. G. Dekany

Palomar Observatory and Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91125

ABSTRACT

The adaptive optics system being tested at the Jet Propulsion Lab will deliver JHK point-spread functions near the diffraction limit of the Palomar 200" telescope (52/68/92 milli-arc seconds). However, as the instrument tips at the Cassegrain focus to track a source, flexure in the non-common optical paths would tend to cause a serious degradation of this spectacular spatial resolution over typical astronomical integration times. Initial tests in the lab and on the telescope indicate that uncontrolled flexure would make the AO beam drift in the focal plane of the science camera by roughly 75 milli-arc seconds in only 15 minutes of tracking, effectively degrading the spatial resolution by a factor of two and making use of the narrowest, highest-resolution spectrometer slits impossible. The relatively large diameter of available deformable mirrors sets a minimum overall scale to the entire AO instrument, and it is difficult to stiffen the resulting large optical mounts well enough to avoid flexure completely. Moreover, changes in ambient temperature are an additional source of differential motion between the science and wavefront-sensing paths that is difficult to eliminate. As an alternative, we report here on a novel and very simple single-beam laser metrology scheme, operating in real time, that yields additive corrections to the tip-tilt offsets for the AO system's fast-steering mirror; these corrections will compensate for the effects of flexure in all of the major optical components in the non-common paths of the Palomar adaptive optics system. The metrology scheme and our AO system are sufficiently generic that this approach should be useful in other systems as well.

1. INTRODUCTION: ADAPTIVE OPTICS FOR THE PALOMAR 200" TELESCOPE

A high-order adaptive optics system has been built at the Jet Propulsion Lab for installation at the f/15.7 Cassegrain focus of the 200" telescope at Palomar. Field testing is well underway[1], and formal commissioning of the instrument is anticipated in the spring of 1999. This system must attempt to correct the effects of an unusually thick and turbulent atmosphere, given Palomar's site at the relatively low altitude of roughly one mile. It should, however, dramatically enhance the performance of a large-aperture telescope of proven reliability.

The overall design of the Palomar system is fairly typical of modern high-order adaptive optics with Shack-Hartmann wavefront sensors. A natural guide star is used as a phase reference, though careful provision has been made during the design for upgrading to a laser guide star mode. The deformable mirror, from Xinetics, is arranged to be optically conjugate to the telescope primary, and has 349 electrostrictive PMN actuators, of which 241 are mapped onto the annular telescope pupil. Actuator throw is ~ 5 μm in surface height, or twice that in wavefront. This is adequate to handle atmospheric phase distortions and the static deformations of the telescope primary itself, which change with telescope pointing, providing the long-term drifts in focus are off-loaded to the telescope control system. There is, as is usual, a fast tip-tilt mirror built into the adaptive optics system to avoid wasting actuator throw on the tip-tilt component of atmospheric seeing, which contains by far the bulk of the turbulent power.

The Palomar adaptive optics system performs wavefront sensing at visible wavelengths to derive corrections for a science beam in the near infrared (essentially the standard J, H, K bands), where atmospheric turbulence amplitudes are smaller and timescales are longer. The wavefront sensor is a Shack-Hartmann with a 16×16 lenslet array of subapertures mapped onto the diameter of the telescope primary. The wavefront-sensing camera must have a very fast readout time, of course, but must also have high sensitivity and particularly low read noise. The Palomar wavefront sensing camera is a 64×64 CCID-15 from MIT/Lincoln Labs, packaged by SciMeasure. Readout rates as fast as 500 Hz are possible, with ~ 6 e^- read noise. Subarrays spanning 4×4 pixels are used to measure tip-tilt angles from each lenslet with an intensity-weighted quadrant detection ("centroid") for each guide star image; conceptually, these local two-dimensional samples of the phase gradient are then used to reconstruct the complete phase function across the pupil and direct the deformable mirror (in practice, the reconstruction is performed on phase gradients rather than on the phase itself).

A drawing of the optical layout of the Palomar adaptive optics system is shown in Figure 1. The larger outline is an optics bench mounted at the f/15.7 Cassegrain focus of the 200"; the beam enters along the optical axis of the telescope, from out of the plane of the Figure, before being picked off by fold mirror FM1. The optical bench is substantial; it is a custom Newport RS4000 measuring 78"×54" and 8.375" thick. There is a second layer of optical components parallel to the optics bench that comprise the "stimulus", a calibration tool that can provide an artificial mockup of the telescope pupil, or of a star viewed through the telescope, while the instrument is in the lab. The stimulus also has various diagnostic tools (e.g. a phase-shifting interferometer) capable of looking back at the components in the main optics bench for aiding alignment and for calibrating instrumental phase distortions, and an artificial turbulence generator for exercising the adaptive optics system in a test mode. All of these capabilities are proving extremely useful for debugging and operating an instrument of the complexity and sophistication of an adaptive optics system.

Tracing the optical path through the components of Figure 1, the beam is first directed onto the off-axis paraboloid OAP1, which collimates it and directs it onto the fast-steering (tip-tilt) mirror FSM, driven on two axes by two fast piezoelectrics actuators. Still in collimated space, the beam next hits the deformable mirror (DM), where aberrations of higher order than tip-tilt are corrected. A fold mirror, FM2, sends the beam to a second off-axis paraboloid, OAP2, which refocusses the beam at the original f/15.7 onto the infrared science camera (SCI CAM) after reflection from fold mirror FM3. On the way to the science camera, the refocussed beam has passed through an infrared-transmitting dichroic, SSM1, that sends the visible light into the Shack-Hartmann wavefront sensor components drawn at upper right in Figure 1.

The visible beam hitting the dichroic (SSM1) is reflected to a second steering mirror SSM2, which is motorized on two axes (as is the dichroic). In tandem, SSM1 and SSM2 direct the natural guide star image onto a 4"×4" square reflective spot on the field stop (FS), an otherwise transparent substrate, so that it is sent into the wavefront sensor, while the infrared science beam passing through the dichroic is unaffected and is always on-axis. Guide stars may thus be acquired at arbitrary positions with respect to the science object. The field stop is at a focal plane conjugate to that of the science camera; beyond it, light from the rest of the field is imaged in an acquisition camera (ACQ CAM) effectively providing a 480×512 array of 11×13 μm pixels. Not shown in Figure 1 is a special Nikon lens mounted immediately in front of the acquisition camera that adapts the expanding f/15.7 beam to a converging beam at $\sim$ f/2. The acquisition camera may also be used, as a diagnostic, to obtain auxiliary extrafocal images that reveal the second derivative of the wavefront phase across the pupil. Using an algorithm discussed by Roddier[2], a full map of the pupil phase itself may be derived, providing an independent calibration of the static deformations of the components of the adaptive optics system.

The guide star light hitting the reflective patch of the field stop is next collimated in a lens that is shown but not labelled in Figure 1, then passes through a pair of counter-rotating prisms forming an atmospheric dispersion compensator (ADC), and then proceeds to the 16×16 lenslet array (LA) and finally the visible-light wavefront sensor camera (WFS CAM). All of these components are mounted on an optical breadboard to help guarantee their rigid relative alignment, ideally to the few-micron level, and the metrology scheme to be presented later in this paper will treat the wavefront sensor as an internally-rigid unit.

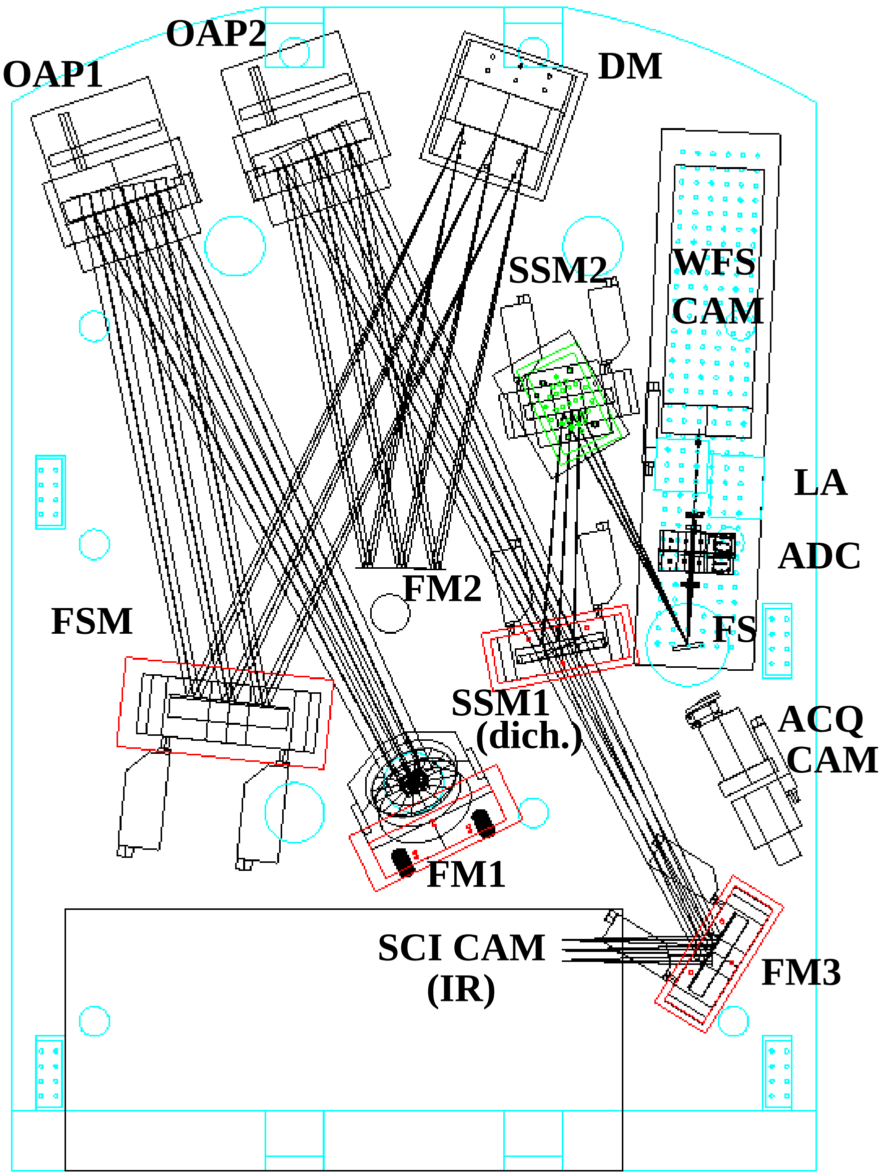

FIG. 1 – Optical layout of the main bench of the adaptive optics system being built at JPL for installation on the Palomar 200" telescope. See accompanying text for discussion. (Adapted from Dekany, 1996[3]).

2. FLEXURE IN THE "NON-COMMON" OPTICAL PATHS

The result of successful operation of the adaptive optics system is a dramatic reduction in the scale of the point-spread function, and this permits the familiar before-and-after pictures demonstrating remarkably high spatial resolution in short exposures. Equally important scientifically, however, is the preservation of that high resolution over the long time intervals typical of most astronomically interesting observations. An entirely new category of science is enabled by the high spectral resolution that results when an adaptively-corrected telescope beam is steered onto a spectrographic slit that is narrower than would be possible without adaptive optics, and this again becomes scientifically most useful only when the beam can be held on the slit over long integration times.

The small size of the adaptively-corrected beam tends to make instrument flexure even more problematic than it is for other large astronomical instruments. However, when the adaptive optics loop is closed, normal operation of the system will automatically correct for flexure in optical elements upstream of the dichroic, before the infrared and science beams are separated. In this "common path", flexures affect the visible light reaching the wavefront sensor in the same way as they do the infrared light reaching the science camera, and so the wavefront sensor sends the appropriate corrective commands to the fast-steering mirror (since these flexure errors are primarily tip-tilt image motions).

Much more troublesome are flexures in optical components located downstream of the dichroic, in the "non-common paths" beyond the point at which infrared and visible beams are separated. Such flexures in the infrared science path will not be detected by the wavefront sensor, and so will go uncorrected. Equally troublesome, flexures in the visible wavefront-sense path will cause erroneous corrections to be applied to the fast-steering mirror, moving the science beam in response to beam deflections suffered in the wavefront-sensor path. In either case, the effect will be blurring of spatial resolution in long-exposure astronomical images, or gradual motion of the telescope beam off of the spectrograph slit if slits as narrow as the nominal high-resolution limit are used.

The formal flexure design goal for the Palomar adaptive optics system was set with realistic astronomical integration times, typically ranging from several minutes to an hour, in mind. Our current baseline is to control or compensate for beam deflections due to non-common path flexure to a level resulting in spot motions on the science camera of no more than a small fraction of the diameter of the Airy spot (say 10 milli-arc seconds equivalent motion on the sky) in 20 minutes. This roughly corresponds to 10% of the diameter of the K-band Airy disk, and is equivalent to about 4 μm of beam motion in the f/15.7 science focal plane (or field stop focal plane). When flexure errors are reduced to this level, they will be smaller than anticipated errors of fitting the deformable mirror. During the design of the adaptive optics system, however, it was estimated that non-common path flexures could induce focal-plane spot motions of 20 to 100 milli-arc seconds on the sky, an order of magnitude above our design goal, and so provision was made for a metrology system to correct for them. The specifics of the metrology design chosen form the subject of this paper.

In Figure 2 we present an abstraction of the optical layout for Palomar's adaptive optics system, highlighting the non-common paths. Though very schematic, this Figure is still roughly to scale insofar as lengths and orientations of optical paths are concerned. The chief sources of non-common path flexure are expected to be FM3, SSM1, and SSM2, since the wavefront sensor components are mounted compactly on a special optics breadboard specifically to combat flexure. The scale of the optical layout is such that the distance from FM3 to the science camera is about 250 mm, and we may use this to convert the flexure specification mentioned above into a limit on flexure-induced tilt of the mirror itself: roughly, the focal-plane image motion of 2 μm would require a tip of FM3 of only about 1 arc second (in the lab, not on the sky). As discussed in the previous section, this flexure in FM3 would cause a large and undesirable motion of the science beam that would be totally unnoticed by the wavefront sensor.

We note in passing that the effects of flexure on system focus may safely be ignored, as the depths of focus in our relatively slow (f/15.7) beams are relatively large. At visible wavelengths, focal depths are roughly $\sim \pm$ 0.25 mm, and mirror translations as large as this due to flexure are not anticipated; in the infrared, tolerances are even greater by a factor of about four.

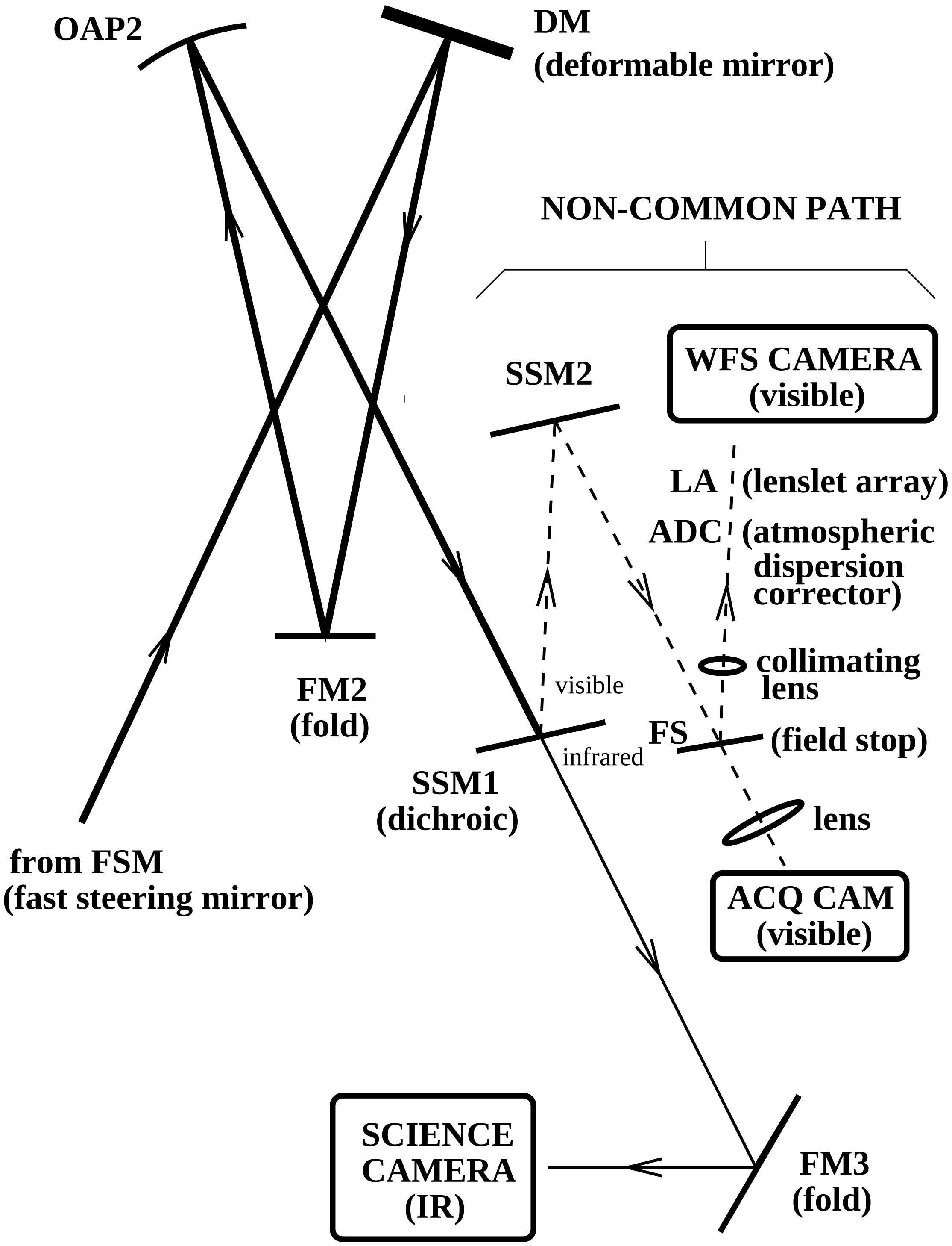

FIG. 2 – Abstraction of the optical layout of Figure 1, emphasizing the optical paths not common to the wavefront sensor (WFS) and science camera subsystems.

3. FLEXURE MEASUREMENTS IN THE LAB AND AT THE TELESCOPE

Experimental tests of the adaptive optics hardware as it was built and during early engineering runs at the telescope have generally borne out the estimates of flexure-induced beam motions discussed in the previous section. In the lab, a 6" Aerotech mirror mount of the kind used in several places on the Palomar adaptive optics bench was loaded with a full-weight mirror, fastened to the bench, and monitored as the table was rotated about its long axis to simulate tracking a source at the Cassegrain focus. Flexures were found to be sufficient to deflect the mirror surface by just under 10 arc seconds when the table was rotated by 15° of elevation (simulating tracking for one hour). If a flexure of this magnitude occurred at FM3, as discussed in the previous section, the beam at the science camera would move by about 24 μm, corresponding to 63 milli-arc seconds on the sky, an order of magnitude out of specification. Similar flexures in SSM1 or SSM2, in the wavefront-sensor path, would cause even larger beam deflections owing to the somewhat longer optical paths from those mirrors to the field stop focal plane.

Another laboratory test of flexure involved loading a 10 pound weight onto a mirror mount, then finding the induced deflections in the surface of the optical table as a function of distance from the mount. Surface deflections were roughly 20 arc seconds at a distance of 1 inch from the mount; again, this corresponds to beam motions that are generally an order of magnitude larger than the design specification needed to permit long astronomical integrations without degradation of spatial or spectral resolution.

Tests carried out during early engineering runs with the adaptive optics system at the Palomar 200" telescope, monitoring stellar images on the science camera and the acquisition camera as the telescope tracks the source, confirm flexure-induced beam motions an order of magnitude larger than desired specifications. Preferred directions of image motion are also seen, as might be expected from preferred bending modes of mirror mounts. For observations of a star at a telescope zenith angle of 15°, non-common path flexure will induce image motions exceeding 10% of the K-band Airy disk diameter in a period of about 2 minutes, not 20; i.e., the drift on the sky is about 5 milli-arc seconds per minute. Some mechanical reinforcement of optical mounts has been done, but flexures are, as anticipated, too large to be completely eliminated, and the residual effects will require monitoring and correction.

A traditional approach to dealing with non-common path flexure within the adaptive optics system would be to map out flexure-induced spot deflections over a systematic grid of telescope pointing positions, and apply interpolated corrections to all subsequent observations. This method is familiar and used to assess flexure in many large astronomical instruments or in telescopes themselves. A reasonable sampling density would require a grid spacing of about 15°, in which case sky coverage down to 30/60/75° away from the zenith would require measurements at 12/46/69 positions. Though somewhat laborious, gathering this data might not be excessively time-consuming if the correction table could be counted on to remain constant over long periods of time — preferably over an observing season. This may not be the case, particularly when the effects of short-term temperature changes are considered.

4. CORRECTION FOR FLEXURE WITH LASER METROLOGY

As a more convenient option than tabulating flexure in a separate calibration step, we have investigated the used of metrology laser beams to probe the positions of instrument mirrors in real time or nearly in real time. It can be difficult to disentangle the effects of flexures in individual optical elements from observations of their cumulative effect on the metrology beam unless a large number of beams are used or the beams trace paths very similar to those of the science/wavefront-sensing beams of interest. Otherwise, a given angular deflection of a mirror will yield arbitrary beam deflections depending on the distance from mirror to image plane. A number of schemes were considered and found to be unworkable or overly cumbersome before we arrived at a simple scheme that follows the second of the two tactics mentioned above: it arranges for the metrology path to be so similar to the non-common paths being monitored that disentangling the effects of individual elements is not required.

The key elements of the favored metrology scheme are shown in Figure 3, superposed on part of the schematic diagram of Figure 2. The metrology laser beam is launched by an optical fiber specially built into the focal plane of the science camera, and arranged to be rigidly fixed with respect to the imaging-mode field center or spectroscopic-mode slit. A corner cube is positioned in the region of FM2, where the adaptive optics beam and the metrology beam are collimated.

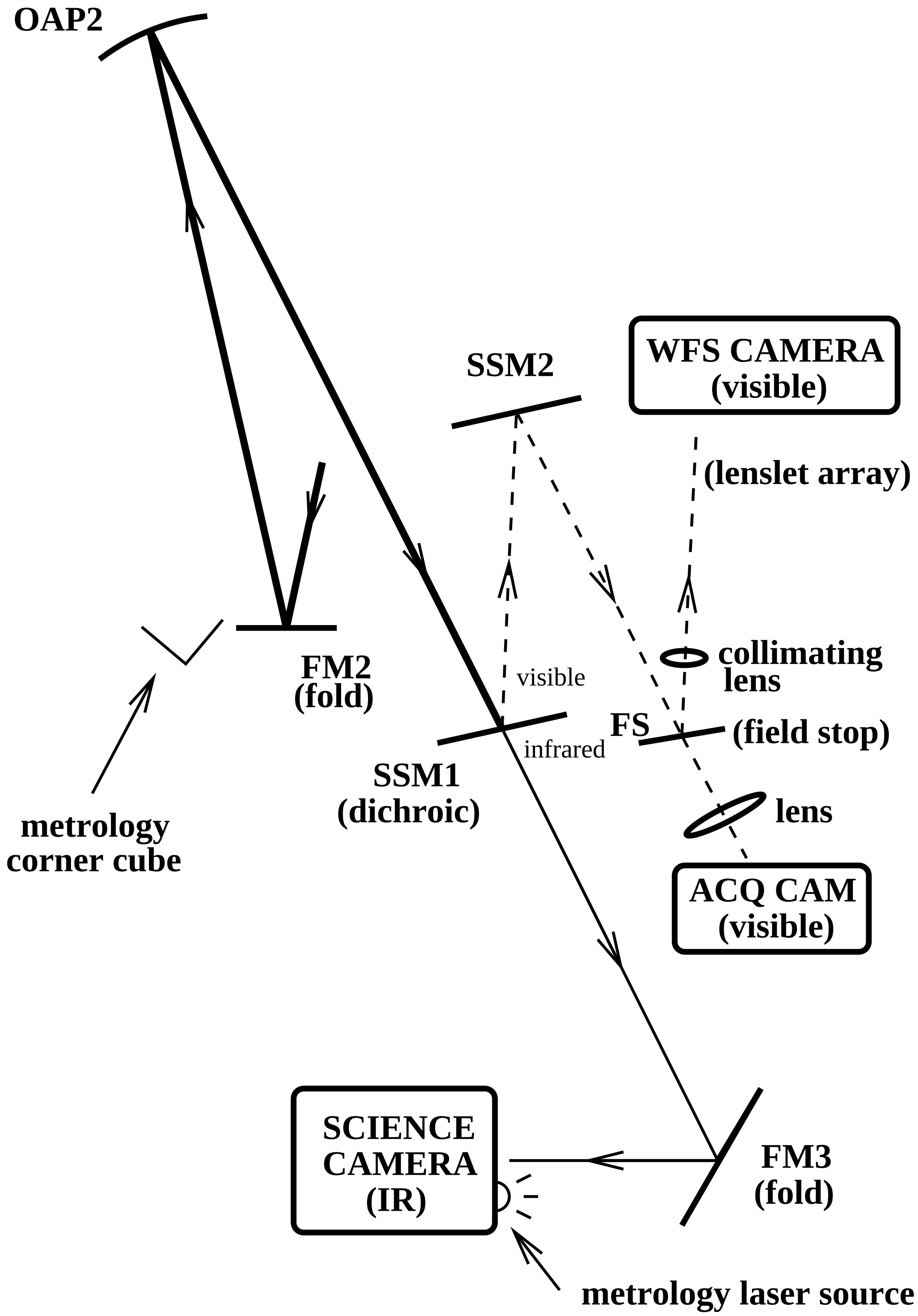

FIG. 3 – As in Figure 2, but slightly simplified to further emphasize the non-common optical paths. Also shown schematically are the main laser metrology components: a corner-cube mounted on FM2, and a quasi-isotropic laser source mounted in the focal plane of the science camera.

To understand the operation of the proposed metrology scheme, imagine first that there were no dichroic. Then the metrology laser beam would be retroreflected to focus again on its source, regardless of flexure in any of the components. With the visible-reflecting dichroic in place, only about 5% of the laser light will even reach the region upstream of the dichroic, but the portion intercepted and returned by the corner cube will for the most part be diverted to the acquisition camera. There, the spot will come to a focus in the plane of the field stop, since this is conjugate to the science camera focal plane. The laser spot will provide a reference for the position of the laser source built into the science camera, and hence, up to a fixed offset, to the field center of the science camera itself; this reference incorporates the effects of flexure in both non-common paths.

Because the wavefront sensor subsystem is built to be internally rigid, and is adjacent to and rigidly located with respect to the acquisition camera, the laser metrology spot also provides a reference tying the science camera to the wavefront sensor. The laser spot should be used as a fiducial for the position of the visible wavefront-sensing beam (the image of the guide star): that is, to track and correct for flexure, the adaptive optics system should steer the guide star to remain fixed with respect to the metrology laser spot, rather than fixed on the detector of the wavefront-sensor camera. It is quite straightforward and presents only a small computational load to implement additive supplements to the wavefront-sensor sub-aperture centroid offsets that incorporate this flexure-compensating tracking redefinition.

When this scheme is adopted, the laser metrology system should correct for tips, tilts, and translations of FM3, SSM1, and SSM2, which are expected to be the dominant sources of non-common path flexure. The scheme requires the laser fiber source to be rigidly mounted with respect to the science camera field center, and the numerous components on the wavefront-sensor breadboard to be internally rigid; care has been taken during construction to ensure that both of these conditions are true. The metrology system also corrects for motions transverse to their optical axes of the science camera and of the wavefront sensor optical breadboard as a whole, with respect to the rest of the adaptive optics system. If stray light from the laser prohibits its operation during astronomical integrations, to prevent flooding the wavefront sensor camera, it would cause no significant loss of performance to alternate brief operation of the metrology system with operation of the rest of the adaptive optics system.

5. SOME DETAILED DESIGN ISSUES

An immediate concern with a scheme that passes a visible laser beam or other light source through a visible-reflecting dichroic might be whether the total metrology beam flux reaching the acquisition camera is adequate. For the efficiencies of the coatings in our dichroic, however, this passage merely attenuates the beam on its way to the corner cube to 5% of its initial intensity, and all subsequent reflections are highly efficient. Assuming a 1-inch diameter corner cube mounted in the vicinity of FM2, and a metrology laser source that emits 100 μWatts into an f/5 beam, the intensity of the return beam at the acquisition camera is about 2×10^{-8} Watts, or about 9×10^{10} photons per second; this is easily sufficient for accurately determining the centroid of the metrology laser spot.

The metrology laser beam is launched by a 50 μm-diameter fiber, and will form a 50 μm spot in the plane of the field stop (FS), which is a 1:1 conjugate of the science camera focal plane. In practice, we expect to image the metrology beam in a separate, dedicated camera located in the vicinity of the acquisition camera, since the spot is launched and will be reimaged at a distance of $\sim$ 1.75 inches from the science camera field center, outside the acquisition camera field of view. For typical flexures in the large optical mounts of the adaptive optics system, metrology spot motions are expected to be 2 or 3 μm; the metrology camera has pixels measuring 11×13 μm. It appears desirable to introduce a magnification of a factor of about five in the metrology beam, and the most elegant means of doing this would be to insert a negatively-powered lens slightly upstream of the field stop that would form an image on the metrology camera positioned to one side of the acquisition camera (and roughly five times as far from the lens as the lens has been moved from the nominal focal plane at the field stop). We are now investigating the feasibility of this elegant solution from the point of view of vignetting of the metrology beam by elements of the wavefront sensor; it appears that this approach will work. Alternatively, less elegant solutions using fold mirrors or less optimal magnifications may be tried.

6. CONCLUSIONS

The dramatic reduction of the instrumental point-spread function makes adaptive optics systems unusually sensitive to flexure, and that flexure will seriously degrade spatial and spectral resolution over the long integration times typical of astronomical observations. The most critical elements whose flexures are not corrected automatically by the closed-loop operation of the AO system are those in the "non-common" optical paths, downstream from the dichroic that separates infrared light for the science camera from visible light for the wavefront sensor. We have presented a simple but comprehensive scheme for monitoring the effects of flexures in all of the elements that are expected to experience major flexure in the Palomar adaptive optics system: referring to Figure 3, this scheme should compensate for tips, tilts, and translations of FM3, SSM1, and SSM2, and for tranverse translations of the science camera and of the optical breadboard housing the wavefront sensor.

The metrology system will be installed and tested soon, as the optical fiber for launching the metrology laser was specified at an early stage and built into PHARO, the near-infrared science camera and spectrometer provided by a team from Cornell University. Other metrology components are quite easy to install. The Palomar adaptive optics system is sufficiently generic that laser metrology of the kind proposed here should be useful in a broad class of adaptive optics systems.

7. ACKNOWLEDGMENTS

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