Keck Adaptive Optics Note 762

# Keck Next Generation Adaptive Optics Point Spread Function (NGAO-PSF) Metrics, Characterization, and Reconstruction

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## 1. Introduction

This document describes efforts to be carried out as part of the Next Generation Adaptive Optics (NGAO) development effort related to that system's point spread function (PSF).

We summarize discussions among the key science case authors to determine cost-benefit trade-offs (also known as "metrics") related to the PSF seen by the science instrument (Davinci).. In section 2 we summarize discussions related to the potential scientific benefit of characterizing the shape and the stability of the PSF. In section 3 we discuss reconstruction. In conclusion, in section 4, we discuss future plans for both efforts.

## 2. Scientific benefits of PSF stability and characterization

The overall quality of the PSF subdivides into at least 12 components, everything from the spatial stability of Strehl, to the temporal stability of enclosed energy (see table 1). Which PSF component provides benefit to a particular science case [1], we see, is highly variable from case to case.

For example, for the Galactic Center (GC) astrometry case, stability of the spatial variation of the full 2D PSF, with all the bumps and wiggles, is needed across the entire field; and it is needed for the duration of the relatively short (~1 minute) exposure time. But wavelength dependence is not necessary for this case [2].

On the other hand, some extra-galactic integral field unit (IFU) studies only need the Strehl and full-width half-maximum (FWHM) information (or, in some cases, the one-dimensional PSF). For these science cases wavelength information is more important. Also, exposure times are longer, so, temporal stability means something else for this science case. For example these studies need only the time-averaged PSF every (approx.) 15 minutes. Spatial variation is also not important for these small IFU fields (noting, however, that the PSF needs to be appropriate for the IFU's specific location in the focal plane, which may be off axis) [2].

Table 1 summarizes, for each science case, which components are important and, for those components, what type of stability is needed.

| Science Case | Science Case Sub-component | Strehl | | | FWHM | | | 1D PSF † | | | 2D PSF | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta d$ | $\Delta t$ | $\lambda$ | $\Delta d$ | $\Delta t$ | $\lambda$ | $\Delta d$ | $\Delta t$ | $\lambda$ | $\Delta d$ | $\Delta t$ | $\lambda$ |
| 1. Galaxy Assembly and Star Formation History | a. Internal kinematics | ❑ | ❑ | ✔ | ❑ | ❑ | ✔ | ❑ | ❑ | ✔ | ❑ | ❑ | ❑ |
| | b. Small scale structure | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| | c. Star formation | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| 2. Nearby Active Galactic Nuclei | a. BH demographics | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| | b. M-σ relation | ❑ | ◧ | ◧ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| | c. Stellar pops, etc | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| 3. Precision Astrometry: Measurements of General Relativity Effects in the Galactic Center | a. Non-Keplerian | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ✔ | ✔ | ❑ |
| | b. Dark Matter Halo | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| | c. Radial Velocity & Sepctral Type | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ✔ | ✔ | ❑ | ❑ | ❑ |
| 4. Imaging and Characterization of Extrasolar Planets around Nearby Stars | a. Cool & faint | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| | b. SFR young stars | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| | c. | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ |
| 5. Multiplicity of Minor Planets | a. Size and shape | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ✔ | ❑ |
| | b. Density | ❑ | ✔ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ✔ | ❑ |
| | c. Composition | ❑ | ✔ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ❑ | ✔ | ❑ |

**Table 1.** For each NGAO science driver [1], an indication of whether that program would benefit from knowledge of the stability of a particular component of the PSF. For each of four common, yet distinct, figures of merit (Strehl, full-width half-maximum (FWHM), azimuthally averaged (1D) PSF, and the overall 2D PSF), we consider three orthogonal views of its stability: spatial stability across the field of view (Δd), temporal stability (Δt), and wavelength stability (Δλ).

A careful characterization of the PSF would primarily benefit observing planning (i.e., efficiency) and published uncertainties. For example, if NGAO documentation could include the statement: "If the independent seeing measurement obtained from the MASS/DIMM monitor varies by no more than 20% during a two-hour exposure, then the Strehl will vary by no more than 5% during that same time interval," then observers could better estimate how much precious telescope time should be allocated to observing nearby point sources. PSF characterization will *not* result in fundamental new information gleaned from the data collected with NGAO; as might occur from PSF reconstruction (see section 3.1 below). It will not, for example, result in a new companion discovery or the better orbit determination of a recently discovered companion.

However, that said, the scientific benefits resulting from improved efficiency and/or improved uncertainties should not be understated. As an example, adaptive optics studies to obtain high spatial resolution studies in the near-infrared of extragalactic sources (e.g., distant galaxies, AGN, supernovae, gravitational lenses, etc.), rely on having spatially stable, temporally stable, and well characterized PSFs. Without such reliable information, observers have difficulty deconvolving the subcomponents of galaxies to measure, e.g. the sizes, brightness, radial surface brightness, shapes of bulges and other compact parts, in distant galaxies. Currently, observers in this field using the existing Keck LGS system, estimate errors by crudely adopting a plausible range of PSFs (since they do not know the actual PSF) and then measure the variation in the output measurements. The fields usually do not have bright enough stars to provide the PSF empirically from images and even if they did, observers would need to know the spatial variations of the PSF. [3]

To underscore the importance of completing the metrics effort, however, care must be taken to not invest development effort for PSF stability and characterization in areas where it may not be needed. For example, the science program being conducted with the current LGS system at Keck to determine black hole masses in Brightest Galaxy Clusters (BCG) has shown that improvement to Strehl will dramatically improve the ability to determine the black hole mass at the center of these galaxies (see figure 2), however, preliminary indications from that study show that the uncertainties (approx. 30%) are, to a large degree, unaffected by PSF instability[1]. [4]

[1] *Need to double check this with Nicholas and possibly obtain power-point slide (from 5/13 talk at Keck) that made this point.*

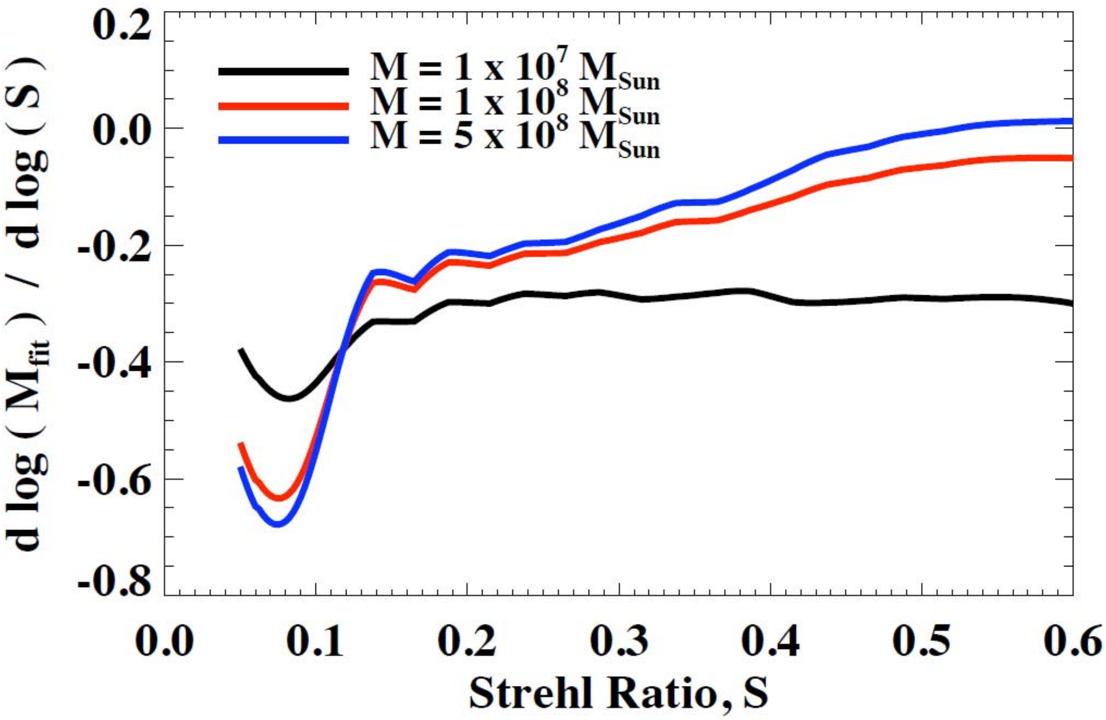


Figure 2. Estimated improvement in black hole mass determination, as a function of achieved Strehl ratio, for Brightest Cluster Galaxies study (McConnell).

## 3. PSF reconstruction

### 3.1 Background

One of the cutting edge technical pursuits of modern day AO system designers is the potential to reconstruct the PSF of the AO system, not from time-consuming and often-inadequate observations of nearby point sources, but directly from the telemetry of the wave-front sensor (WFS) itself. A continuous, or nearly continuous, reconstruction of the PSF during the observation would not only address the characterization and stability issues of the previous section, but would actually improve image quality after the fact through application of one of several proven deconvolution packages (see table 2).

| Package | Reference |
|---|---|
| Mistral | Fusco, T. (2002) |
| IDAC | Jeffries, S. (1993) |
| AIDA | Hom, E. (2007) |

**Table 2.** Software packages used for deconvolution. Each of these packages can be used in a mode in which a PSF measurement can be used to partially remove distortion resulting from PSF imperfections to improve the quality of the science data.

The degree of difficulty of PSF reconstruction varies greatly depending on the science program and the type of AO system. For example, PSF reconstruction performed during observation of a bright compact source (without the need of offset tip-tilt stars and a laser) is a far more tractable task than performing that same process during the observation of a distant galaxy surrounded by faint reference stars and lasers. The type of AO system also affects the degree of difficulty. A difference in the intrinsic noise properties inherent in Shack-Hartmann versus curvature-based AO systems may favor the latter for PSF reconstruction. [5]

A second challenge must be addressed before a facility, operational, system of PSF reconstruction can be provided reliably to guest observers: The raw telemetry data must be included in the take-home data set of the observer, along with the stand-alone software tools necessary to convert that raw data into a PSF representation that can be easily ingested by a standard deconvolution package (see Table 2). The take-home data set must be of a practical size. Based on experience with the current Keck AO system, this will have to be a deprecated subset of the several terabytes of telemetry data that NGAO will produce on a single night. That deprecated data set (sometimes referred to as the 'Reader's Digest') will likely be generated via a specialized SQL query invoked automatically after sunrise on each science night. The product of that query will then be saved in the same data directory containing the science FITS images collected using Davinci.

Although developing a system to reliably and automatically generate this Reader's Digest version of the telemetry stream is a much smaller task than development of the reconstruction tools that will operate on that data, it is also required sooner than those tools and will therefore be given high priority among the software development tasks comprising this effort.

As an aside, efforts are underway to provide this mechanism for the existing Keck AO system in anticipation of reconstruction tools becoming available for that system (see 4.2 below).

## 3.2 Scientific Benefit of PSF Reconstruction

TBD [includes write-up of 28mar2008 observing (orbit determination) example]

# 4. Future Plans

## 4.1 Future plans for Metrics

During the detailed design phase, a subsystem to provide appropriate levels of PSF characterization and stability will be specified and designed. Several phases comprise this effort.

First, the best bang-for-the-buck (i.e., "metrics") will be determined. This phase includes completing table 1 and, for each checked box in the table, quantifying the effort. As an example of how a given checked-box from table 1 might be quantified, consider figure 2: Although this figure pertains to absolute Strehl, and not stability or characterization, a similar plot could be generated that would indicate a quantified science result anticipated for various levels of improvement to PSF stability. From that quantified view, a subset of the "columns" will be chosen (naively, for example, the columns with the most checked boxes) to determine high-level goals for the system. From discussions thus far, "temporal stability of Strehl to within 2% over 15 minutes" and "spatial stability of 2d PSF over a 40 arc-second field to within 5% of that seen on axis" are potential candidates for inclusion in this subset[2]. From that set of goals, the hardware and software necessary to achieve them will be specified and designed. Hardware will include internal calibration sources and instrumentation to monitor possible sources of PSF instability (for example, vibration). Software will include control system components required to operate any hardware installed to monitor sources of instability, simulation packages, and visualization tools. Lastly, observation simulators and documentation will be provided on web pages for use by observers.

## 4.2 Future Plans for PSF Reconstruction

The effort to provide NGAO PSF reconstruction will take place across four phases.

The first phase, a demonstration effort being built for the current Keck AO system, is currently underway. Laurent Jolissaint has completed groundwork at Gemini Observatory [6], and will now turn his attention to completing a similar, NGS on-axis, capability at Keck. The Keck work will, however, be based on previous efforts by Ralf Flicker and David le Mignant [7]; rather than the 2003 CFHT system (Jolissaint) as was used as a basis for the recently completed Gemini work.

This first phase being built for the existing Keck AO system also includes work to provide the observers with the 'Reader's Digest' deprecated data set described in 3.1 above. A web page to collect information needed to program the early-morning query, and, subsequently, save that information into the observers'

[2] *Need to check this against what might already be in contour*

data area, has been created. Also, preliminary discussions to determine the method for including the data set in the observatory's *Savier* backup-archive system [8] have begun.

Subsequent phases will all pertain to the NGAO system. Based on the demonstration project described above, NGS on-axis will first be addressed, along with (in parallel) the beginning of the LGS on-axis system.

Once NGAO NGS on-axis is complete, the effort to provide LGS on-axis will be completed and, in addition, a study based on experiences thus far will be initiated to determine the feasibility of providing PSF reconstruction for the full-up, multi-LGS, off-axis case.

Depending on the results of that feasibility study, efforts to complete the 'Holy Grail' of PSF reconstruction for full-up NGAO will (possibly) begin.

## 5. References


1. *Keck Next Generation Adaptive Optics Science Case Requirements Document*; KAON 455.
2. Personal communication; J. Lu.
3. Personal communication; D. Koo
4. Personal communication (and material from 13may2010 presentation at Keck); N. McConnell
5. Personal communication; O. Lai.
6. *PSF Reconstruction Project Opera Project, First Results;* Laurent Jolissaint, Aquilaoptics, Switzerland, May 14, 2010
7. *PSF reconstruction for Keck AO Phase 1 Final Report*; Ralf Flicker
8. http://www.keck.hawaii.edu/software/savier (internal web site at Keck)