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Point spread function determination for Keck adaptive optics: overview

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ABSTRACT

One of the primary scientific limitations of adaptive optics (AO) has been the incomplete knowledge of the point spread function (PSF), which has made it difficult to use AO for accurate photometry and astrometry in both crowded and sparse fields, for extracting intrinsic morphologies and spatially resolved kinematics, and for detecting faint sources in the presence of brighter sources. To address this we initiated a program to determine and demonstrate PSF determination for science observations obtained with Keck AO. This paper aims to give a broad view of the progress achieved in implementing this capability for Keck AO science observations.

The concept and the implementation are briefly described. The design and development of prototype operational tools for automated PSF reconstruction is presented in detail. On-sky performance of the technique is discussed by comparing the reconstructed PSFs to the NIRC2 science camera's PSFs. The PSF algorithm development for this program is presented in this conference in a separate paper (Jolissaint et al. 2016).

Keywords: adaptive optics, point spread function reconstruction, Strehl, PSF stability, W. M. Keck Observatory

1. INTRODUCTION

The Keck AO systems provide near diffraction limited images in the near-infrared with the OSIRIS instrument on Keck I (Larkin et al. 2006), and the NIRC2 and NIRSPEC instruments (McLean et al. 1998) on the Keck II telescope. The W. M. Keck Observatory (WMKO) has endeavored to continually improve the capabilities of these systems ever since providing the first NGS and LGS AO facilities on a large telescope. One such improvement is the implementation of the PSF reconstruction facility.

One of the primary scientific limitations of AO has been lack of knowledge of the PSF, which has made it difficult to use AO for quantitative astronomy. The PSF determination project at the Keck observatory addresses this limitation. The PSF must be determined for each science exposure and as a function of position in the science exposure as the turbulence and the degree of AO correction varies with time.

The project is broadly classified into two parts: on-axis and off-axis cases. The on-axis PSF determination has been developed through collaboration with the University of Applied Sciences Western Switzerland and WMKO (Jolissaint et al. 2014; Ragland et al. 2014). The off-axis PSF determination has been developed by the UCLA Galactic Center group in collaboration with WMKO and the University of Hawaii (Fitzgerald et al. 2012). The design of an overall operational tool to compute the on- and off-axis PSFs in semi-real time is being developed at WMKO (this work).

The focus of this paper is to provide an overview of the program and details on the operational tool and computational infrastructure development. The details on the algorithm development are presented in a separate paper in this conference by Jolissaint et al. (2016). The outline of the paper is as follows: The concept of the PSF reconstruction is briefly described in Section 2, AO telemetry archival in Section 3, data management and workflow in Section 4, computational and data storage facility in Section 5, highlights of the on-axis results in Section 6, off-axis algorithm development in Section 7, and a brief summary and future plans in Section 8.

2. THE CONCEPT

Our implementation is based on the approach introduced by Jean-Pierre Véran et al. (1997). In simple terms, the observed PSF can be approximated as the convolution of the instrument PSF (telescope and instrument optics) and a PSF associated with the residual post-AO wavefront errors. i.e. $PSF_{tot} = PSF_{instr} * PSF_{AO}$. In the spatial frequency domain: the optical transfer function is $OTF_{tot} = OTF_{instr} . OTF_{AO}$. The OTF_{AO} is defined in terms of residual phase structure function, $D(\lambda\nu)$, as follows: $OTF_{AO} = e^{-D(\lambda\nu)/2}$, where λ is the wavelength of observation and ν is the angular spatial frequency.

The wavefront phase errors are assumed to be composed of complementary and orthogonal components, namely, controlled and uncontrolled modes. The residual errors of the controlled modes are estimated from AO control loop data, and the errors of the uncontrolled modes (fitting errors) are estimated through modeling of astronomical seeing knowing the instrument characteristics. i.e. $D(\lambda\nu) = \sum_{ij} < \varepsilon_i \varepsilon_j > U_{ij} + D_{TT}(\lambda\nu) + D_{FE}(\lambda\nu)$, where $< \varepsilon_i \varepsilon_j >$ is the covariance of the WFS measurements, $U_{i,j}$ refers to spatial correlations of the deformable mirror (DM) modes (the influence functions), D_{TT} ($\lambda\nu$) and D_{FE} ($\lambda\nu$) refer to the tip/tilt structure function and fitting error structure function respectively.

The aberrations not seen by the wavefront sensor are estimated through on-sky phase diversity. In the case of on-axis laser guide star (LGS) AO, two more terms, namely, tip/tilt and focal anisoplanatism are needed. For off-axis cases, additional anisoplanatism terms, estimated through C_n^2 profiles from an on-site MASS/DIMM atmospheric profiler, are added to the OTF_{AO}. More details could be found in Laurent et al. (2014; 2016) and Ragland et al. (2014).

An initial version of the prototype operational tool was developed in the IDL environment through multiple scripts. In order to provide more stability a database and a task scheduler were implemented as a part of the prototype. The major components of the prototype are: (1) computational infrastructure (including storage disks/tapes and servers) and (2) interface software (including IDL wrappers, task scheduler, mySQL database, and an interactive web-based graphical tool. A schematic diagram illustrating various components of the PSF reconstruction process is shown in Figure 1. The top, middle, and the bottom levels show various components developed at Hes-so (Haute école spécialisée de Suisse occidentale), WMKO, and UCLA, respectively.

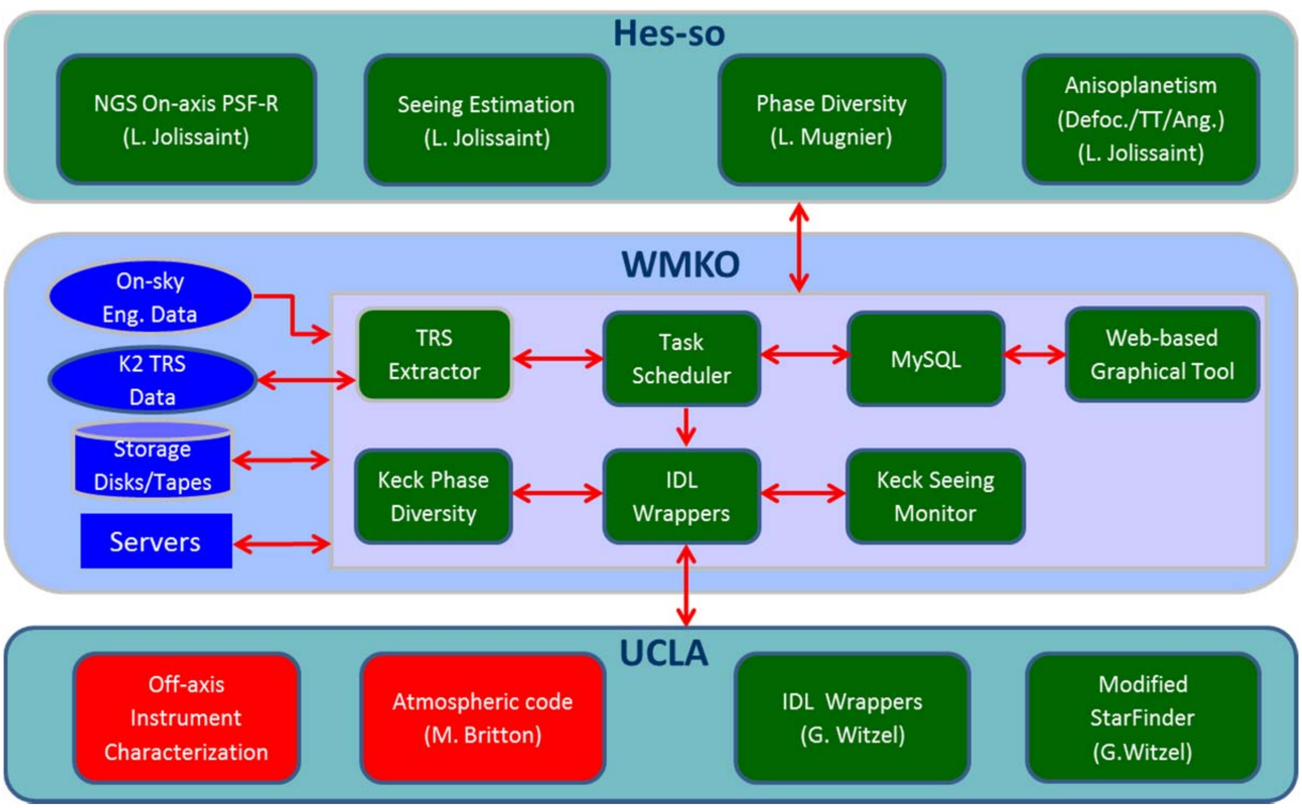

Figure 1: A schematic diagram of the PSF reconstruction process showing various components developed at different locations.

3. AO TELEMETRY ARCHIVAL

The telemetry recording system (TRS) records telemetry data on AO nights. Data is sampled at 10 MHz and saved to a PostgreSQL database on the k#ngwfc-trs server (#:1 for Keck I and 2 for Keck II). The amount of data stored in the database is large enough such that the database disk has to be cleared on a rolling seven day cycle. So, at most, a given night's TRS data is only available for the next six days in the database. To preserve the telemetry data for a longer period of time and to reduce the disk space requirements, the data is selectively retrieved and transferred to disk storage as described below.

A script retrieves and saves TRS data for the integration period of a given science FITS file. The script is started via a cronjob and runs daily. Figure 2 shows the workflow for the process. "gettrsdata" (the top block) is the main IDL wrapper that finds the appropriate FITS files, verifies that they are on-sky images and that the AO loops are closed, then retrieves the TRS data. Retrieval of the TRS data is done using the "gettrs" (the bottom block) which in turn uses the "trsquery" tools, after getting necessary input parameters from the keywords, which is a C-interface to the PostgreSQL database. "trsquery" is widely used within the AO operational software. The processing tasks are currently running on psfrdataserver1 and use local disks for data storage.

The cronjob starts at 8 am daily and the data extraction typically takes a few hours depending on the amount of science data collected the previous night. As the psfrdataserver1 is located at WMKO headquarters while the TRS server is at the summit, the telemetry archival process takes significant network bandwidth in the mornings. This became a serious problem once we started archiving K1 AO telemetry as well. It may be necessary to move the storage server to the summit however it is unclear if the current storage disks (spinning disks) will perform satisfactorily in the summit environment.

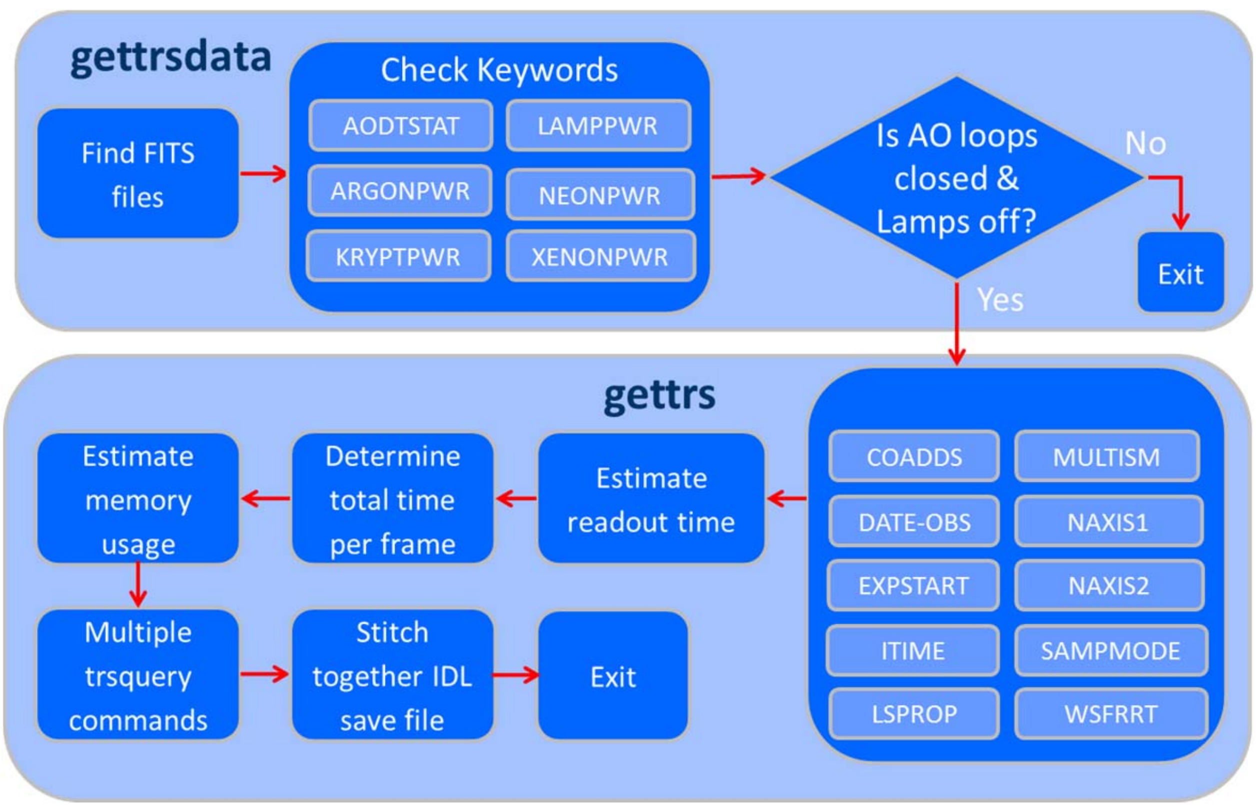

Figure 2: A schematic diagram showing the work flow of the TRS retrieval process. The top level is an IDL wrapper and the bottom level is the actual code to extract the telemetry.

4. DATA MANAGEMENT AND WORKFLOW

To facilitate the processing of archived and new data, a prototype software infrastructure has been developed to collect, ingest, monitor and manage the required science and telemetry data. PSF reconstruction (PSF-R) tasks are scheduled for processing immediately after ingestion into the system. A workflow control task dispatches the scheduled tasks to multiple hosts; depending on available resources up to 48 tasks can be executed in parallel. The task's progress and status can be monitored and displayed via a web-based graphical tool, which can also be used to cancel tasks or select tasks for re-processing. For this tool, MySQL, PHP and JavaScript are used. These tools enable easy monitoring of the status of telemetry extraction and PSF reconstruction processes, and enable easy rerun of telemetry extraction and PSF reconstruction processes, if necessary. The concept of scheduling multiple tasks (one task per each science exposure) on multiple computers across the Keck network guarantees the completion of PSF reconstructions of the science data from the previous night before sunset. Figure 3 shows a snapshot of the status display tool showing number of AO science exposures and the total exposures including the calibration files, if any, on a given AO science night. The tool will be updated to include other information such as number of telemetry files among other things.

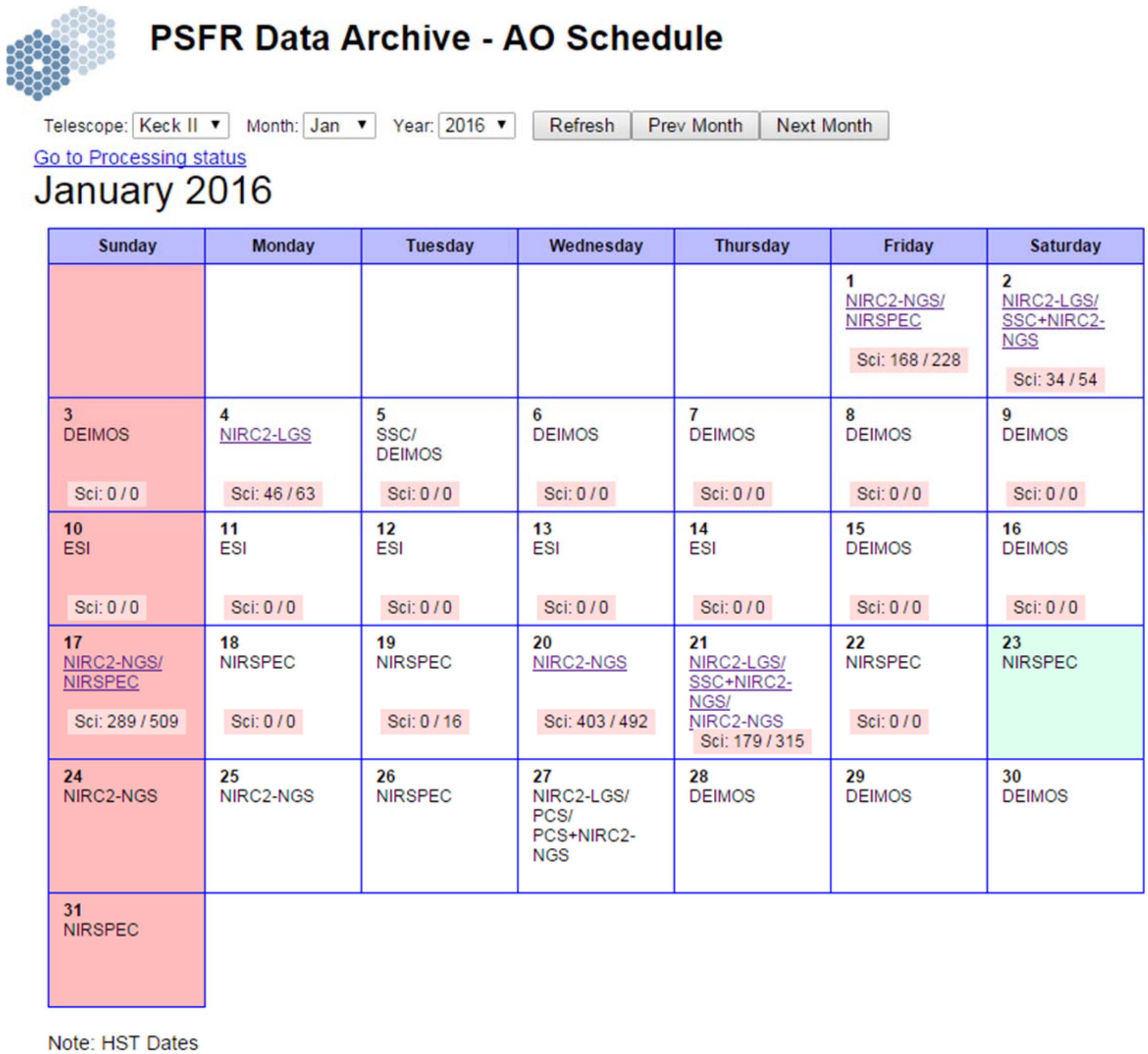

Figure 3: Top level web display showing the status of the archival process in the form of a calendar. Number of science exposures and total number of exposures including the calibration files are displayed for AO nights.

Figure 4 shows a snapshot of the web-based graphical tool showing the status of the PSF reconstruction process. This tool allows scheduling or canceling PSF reconstruction tasks for selected science exposure(s) (or all exposures) on a given night. The above two graphical tools are intended for internal use by the observatory staff to monitor the reconstruction process, reallocate the computational resource, and rerun the computations if necessary.

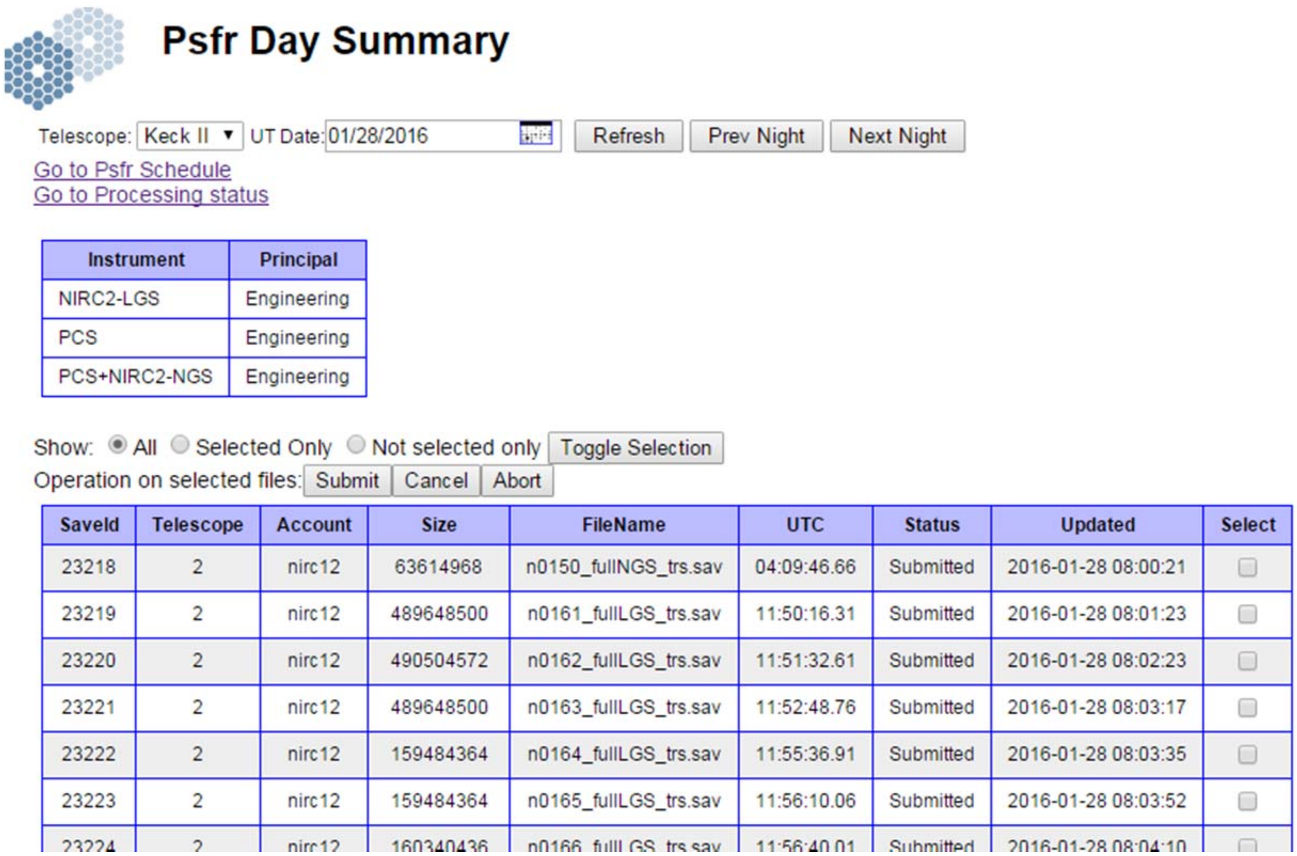

Figure 4: A snapshot showing the status of the PSF reconstruction process.

5. COMPUTATIONAL FACILITY

The computational facility includes (1) the servers used for computation, and (2) the storage system to accommodate at least ~3 years of data readily accessible for PSF reconstruction.

The PSF reconstructions are performed on two computer systems in parallel: (1) a virtual computer system in a Linux environment, and (2) a dedicated storage server, a Linux host, that holds the AO telemetry data and some Keck Observatory Archive (KOA; Berriman et al. 2014) data. Some details on the virtual computing environment are given below.

5.1. Keck VMware Virtualization System

The Keck VMware Virtualization is a generic virtual computing cluster consisting of three Cisco UCS C220 M x86 based servers, a Nimble SC240 with two expansion storage shelves and two Cisco 3750X network switches connecting everything together.

The Cisco UCS C220 M servers are Intel Xeon CPU E5-2665 2.4 Ghz servers (8-core/processor) with 256G's of RAM and have multiple gigabit cables into the Cisco 3750X switch. The Nimble SC240 has two controllers, each with six total gigabit cables connected to the network. This configuration provides multi-gigabit paths between the UCS C220 M servers and the Nimble SC240. Multi-gigabit links provides both higher throughput and redundancy. The Nimble controllers are in an active/passive configuration, such that if the primary fails the backup automatically kicks in. The Cisco 3750X gigabit switches are stacked, acting as a single switch, such that if one switch fails the other will handle the load for the system. The Cisco switches are simultaneously operating together. The configuration is not 100% reliable, but it has many redundancy and disaster recovery features implemented.

vCenter is the heart of the VMWare design; it provides disaster recovery and hardware availability for virtual machines running on the three Cisco UCS C220 M servers. The PSF reconstruction prototype machine vm-sragland is a virtual machine (VM) running in this environment, if the Cisco server hosting vm-sragland dies, vCenter will automatically move vm-sragland to a functional Cisco UCS C220 M (i.e. vm-sragland should not stop functioning as vMotion moves it to a working Cisco server.)

vm-sragland performance has not been formally analyzed. It is currently configured as a 2.4 Ghz, 8-Core, 16 Gbyte RAM server with access to 300G of Nimble Storage, and so far provides acceptable performance. Memory, number of cores, and storage can be increased on vm-sragland. The only exception is that the Nimble is already tapped out for space and adding 1T plus of space has also caused problems for other data reduction systems, so it is not advised at this time.

The VMware environment is great for prototyping the PSF-R system and does not cost anything extra for the program. The final PSF-R may need to be dedicated fast physical servers with local storage. The current storage server is described in the next section along with storage disks and tapes.

5.2. Data Storage

A major component of the PSF-R hardware system is storage. The AO telemetry collected during science exposures are archived to the PSF-R data storage system for PSF reconstruction. In some cases, the data will be required if the PSF-R application is modified and we need to re-process the existing/old data. The architecture of the PSF-R storage system is presented in Figure 5.

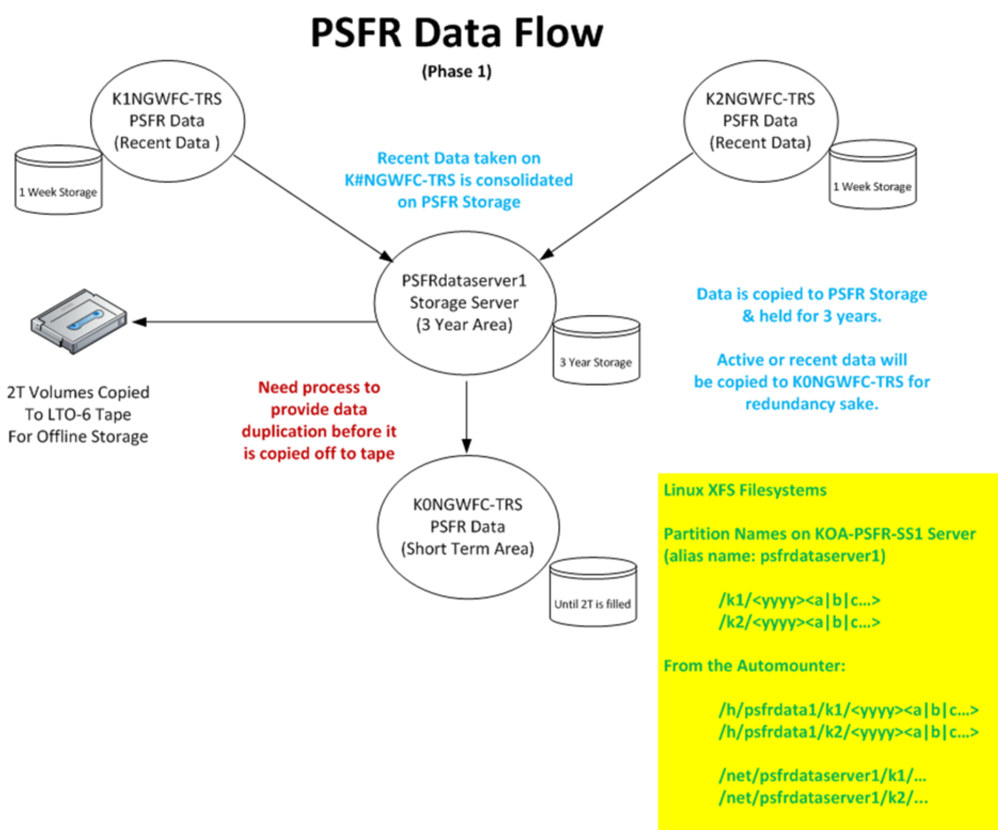

Figure 5: A schematic diagram showing the data flow of the AO telemetry data for PSF-R.

5.2.1. Storage Requirements

The storage requirements are listed below:

- Capacity estimate is 10TB/year/telescope and needs to be available for at least 3 years, therefore a total of 60TB total storage for Keck 1 and Keck 2. Starting off with a smaller capacity is acceptable.
- The data is a collection of files. It is not a database application.
- The data is not part of telescope operation or live data. It will be moved from the primary collection area to this storage area for the long term storage.
- Collected data will not be modified, so the data is static and read-only.
- The nightly AO telemetry data should be transferred to the storage disk before noon (HST) the following day. This would give necessary time in the afternoon for lev0 data processing.
- An offline copy of the data for disaster recovery purposes is needed.
- The storage area needs some redundancy designed into the system, a RAID configuration will be necessary to address single or multiple disk failures.

With these requirements in mind, three systems were compared. The Nimble SC240 is the high end storage solution with fast I/O and costs the most per terabyte. It is used on the VMWare system at WMKO. The ASL Unix server with two external Triton 12S storage shelves is modeled after existing systems at WMKO. This model has been successfully used for over a decade. And the ASL Sovereign system is also a Unix (specifically Linux) server with a chassis that has 36 disk slots, replacing the need for external storage shelves like the Triton 12S storage shelf. All solutions have some form of RAID and a method to monitor/manage the system and send email alerts when there is a problem. We selected the ASL Sovereign solution based on features, management and price. Price was a huge factor since the data is mainly static and the I/O is not a high priority (at least for the prototype system.)

5.2.2. Selected Storage Implementation – ASL Sovereign 4898SRT

The ASL Sovereign 4898SRT storage server runs Centos 6.x Enterprise Linux (ASL tested and delivered the unit with Centos 6). The Centos OS is stored on SuperDOM flash memory, not on an SSD or spinning disk. This server currently has 24 times 4TB SATA disks for data storage; there are 12 empty disk slots. It has two 3Ware disk controllers, 12 disks/controller to balance the disk load. Each controller is configured as an eleven disk RAID-6 array plus one hot spare disk. A RAID-6 array with eleven disks means that nine are for data and two for parity, therefore you can lose up to two disks before you lose the array and all the data. On a 4TB disk, you receive about 3.7TB usable, therefore nine disks times 3.7TB result in approximately 33TB of usable storage. The 33TB storage space is carved up into smaller volumes so that we can freeze the data and back it up to LTO-6 tapes for the offline storage requirement.

The unit is shared by both the KOA and PSF-R projects, therefore it is not recommended that we use it as an application server and only use it as an NFS storage server. Nevertheless, we have been experimenting with this server as a part of the distributed cluster across the network for PSF reconstruction.

The NFS directory structure uses the auto-mount configuration currently implemented at Keck. This structure allows for future NFS Servers to be added to the system, new links will be created as necessary and will be transparent to the users. 10T/yr/telescope is an estimate; therefore the specific <yyyy><a|b|c|c> will be created as necessary.

5.5.3. Storage Partitions and Offline Backups

A new LTO-6 tape drive has been procured and physically connected to the Sovereign 4898SRT server for data backup as the existing one (a LTO-6 tape drive) is already heavily used for science operations; moreover a local LTO-6 tape drive would reduce network traffic.

The LTO-6 tape drive is a 2.4TB non-compressed data storage device; therefore we have configured NFS storage volumes to be approximately 2TB each. The goal is to be able to store a NFS volume on a single tape.

6. HIGHLIGHTS OF THE ON-AXIS RESULTS

The reconstructed NGS AO PSFs are compared with the sky PSFs in Figure 6 (left) and the 1D intensity profiles through the PSF peak are compared in Figure 6 (right) to validate the algorithm. The sky PSFs were taken with the NIRC2 camera with Fe II filter (λ_{eff} = 1.6455 µm; δλ= 0.0256 µm). The tip-tilt star was on-axis for these observations.

Typically for the high Strehl ratio case, the overall shape of the reconstructed profile matches well with the sky PSF, but the Strehl ratio differs by as much as ~15%. Even for the low Strehl ratio case, the profiles match well between the reconstructed and the sky PSFs for most of the datasets. However, there are datasets - especially the ones taken with high telescope wind shake – that show discrepancies.

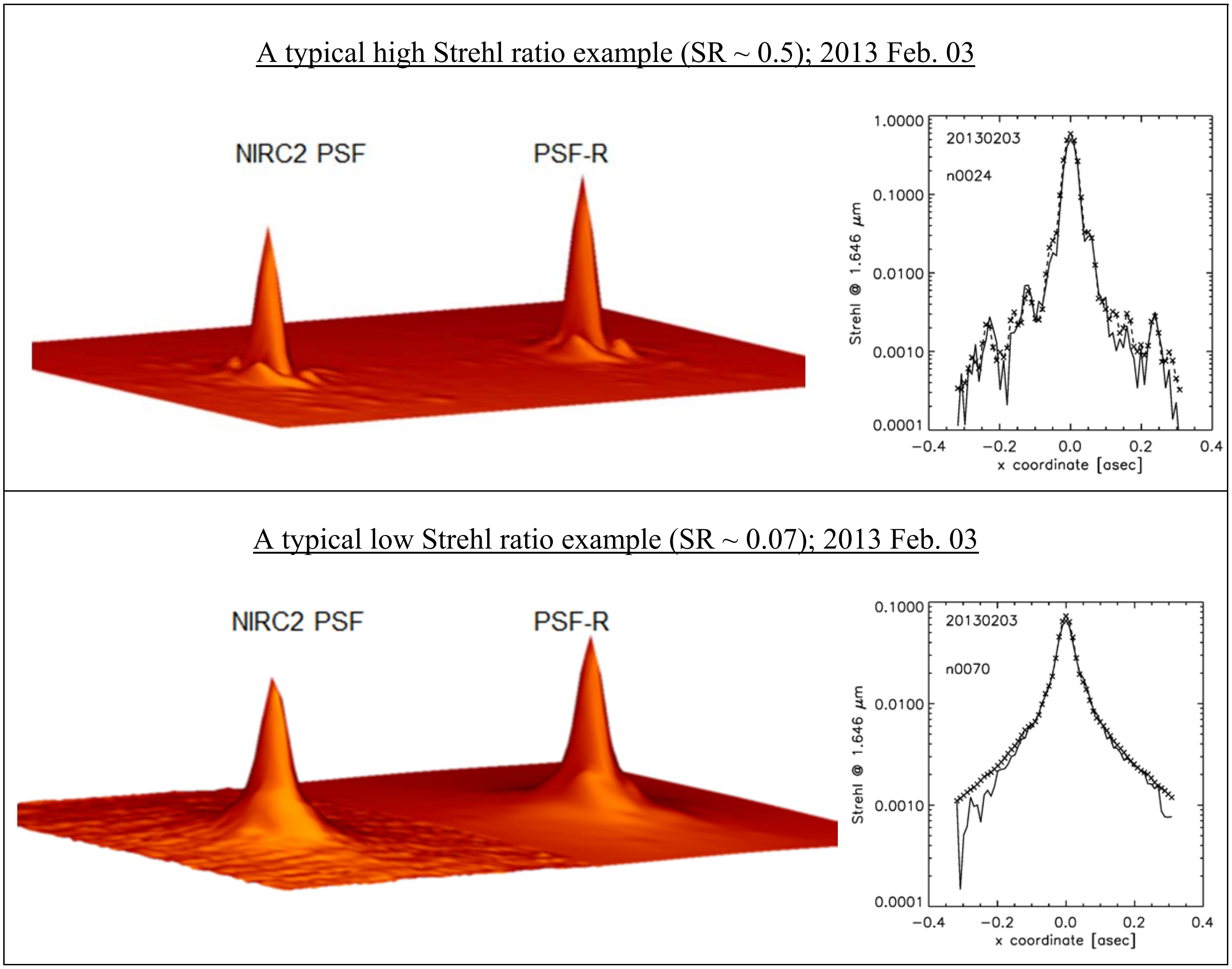

Figure 6: Left: The reconstructed NGS PSFs are compared with the sky PSFs for a typical high Strehl ratio and a low Strehl ratio case. The images were taken at 1.655 µm. Right: A scan across the PSF through the peak is shown in logarithmic scale. The cross symbol represents the sky profile and the solid line represents the model profile.

The reconstructed LGS AO PSFs are compared with the sky PSFs in Figure 7 (left) and the 1D intensity profiles in Figure 7 (right). As in the case of the NGS observations, the sky PSFs were taken with the NIRC2 camera with Fe II filter (λeff = 1.6455 µm; δλ= 0.0256 µm). The tip-tilt star was on-axis for these observations. Again, the reconstructed PSFs match fairly well with the sky PSFs. Also shown in this figure (right) is the reconstructed profiles ignoring the focal anisoplanatism.

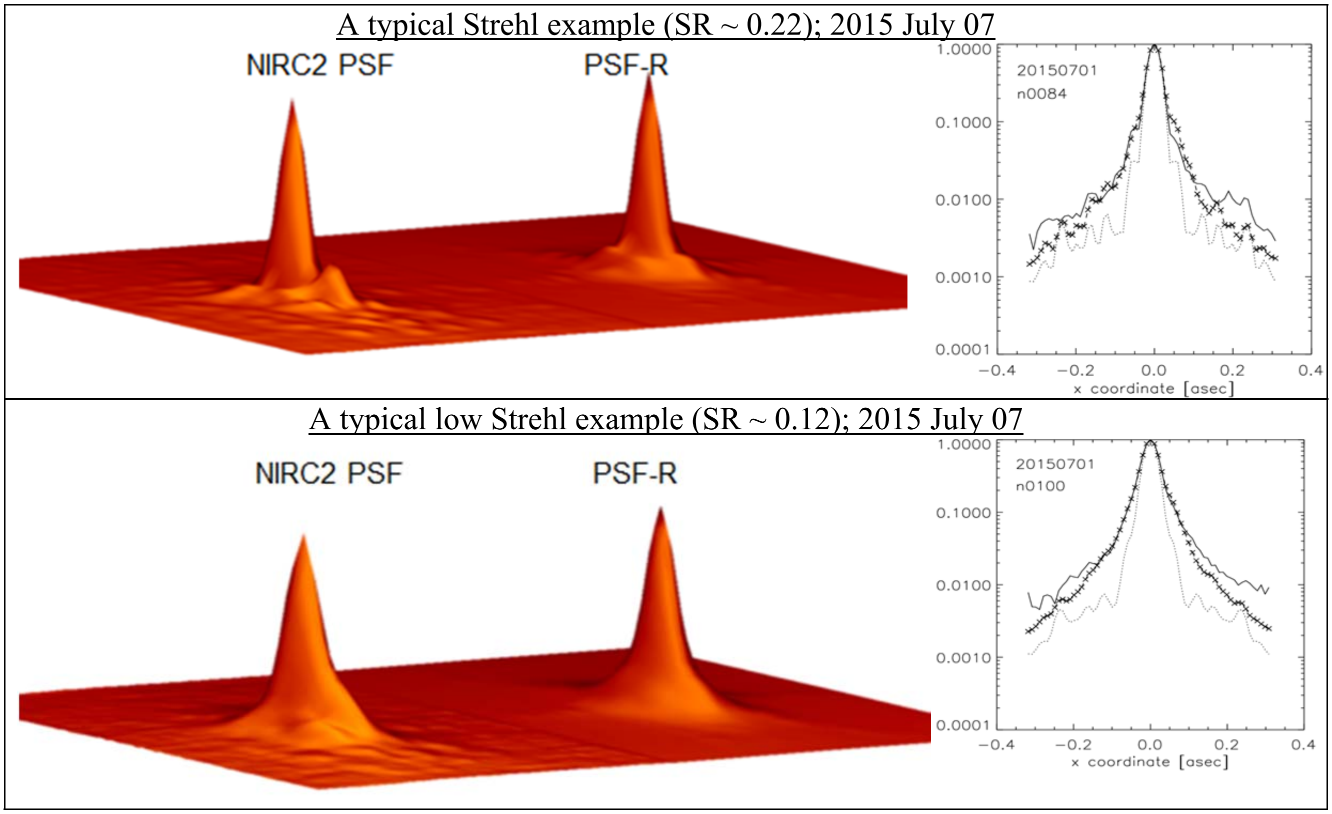

Figure 7: Left: The reconstructed LGS PSFs are compared with the sky PSFs for a typical Strehl ratio and a low Strehl ratio case. The images were taken at 1.655 μm. Right: a scan across the PSF through the peak is shown in logarithmic scale. The cross symbol, the solid line, and the dotted line represent the sky profile, the model profile and the model profile ignoring focal anisoplanatism.

7. OFF-AXIS ALGORITHM DEVELOPMENT

Off-axis PSF prediction tools are developed at UCLA primarily for astrometry and stellar orbits at the galactic center. The Galactic Center Group @ UCLA is in the final year of a project to optimize the extraction of AO astrometry and photometry by incorporating measurements of the Earth's atmospheric turbulence profile and instrumental aberrations to build a model of the PSF spatial variations in every AO image obtained with the NIRC2 instrument on the Keck II telescope. This project, entitled AO Optimization (PI: A. M. Ghez) is funded by the W. M. Keck Foundation. The ultimate objective of the AO Optimization project is to apply these methods to past and future observations of stars near the supermassive black hole (SMBH) in order to use their orbits to test General relativity.

The UCLA team has developed algorithms to predict how the PSF varies and incorporated them into a new software package: AIROPA (Anisoplanatic and Instrumental Reconstruction of Off-axis PSFs for AO). This software package makes use of independently measured atmospheric data like MASS and DIMM profiles and predicts the differential OTFs between different field positions. Based on ARROYO (M. Britton 2006), a set of C++ class libraries that aim to support simulations of electromagnetic wave propagation through turbulence and through optical systems, AIROPA includes C++ tools for predicting both natural guide star and laser guide star PSFs, as well as application program interfaces (APIs) for IDL. Furthermore, it provides extensive IDL modules for Fourier-based PSF manipulation and for PSF modeling from any externally generated aberration maps. These IDL routines and APIs are integrated with a modified version of StarFinder.

The goal is to transfer AIROPA software to WMKO to be used for other off-axis science programs as well. A modified version StarFinder (StarFinder_AIROPA) and related IDL interface routines have been successfully installed at WMKO. We anticipate installing and testing the complete software suite including the code for modeling atmospheric anisoplanatism, which is essential for off-axis PSF reconstruction, at WMKO in 2016.

8. SUMMARY AND FUTURE PLANS

The on-axis PSF reconstruction algorithm development is nearly complete and the code is being validated. An earlier version of a part of the off-axis PSF reconstruction tools has been transferred to WMKO. The complete software package is expected to be tested at WMKO this summer. Prototype high level operational tools to use the above PSF reconstruction algorithms have been developed and initial tests were carried out.

The next steps are:

(1) Release the final version of the on-axis PSF reconstruction algorithms and complete validation of the algorithms with the engineering data (Feb. 2016.)

(2) Collect test data for the prototype operational tool in preparation of an operational tool design review.

(3) Validate the algorithms against the maos code (developed by Lianqi Wang at TMT) through collaborations with LAM and TMT AO teams in order to gain confidence in our algorithm and share the lessons learned.

(4) Complete tradeoff studies such as standalone server versus VM servers for PSF computations, Keck seeing tool versus Jolissaint's tool, Keck phase diversity tool versus Mugnier's tool, etc.

(5) Integrate off-axis components developed at UCLA and validate the algorithm with on-sky engineering data.

(6) Carryout science verification.

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The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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