# Atmospheric Profiler for NGAO: Initial Requirements and Design

**KECK ADAPTIVE OPTICS NOTE 552**

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## ABSTRACT

This note outlines the requirements and a design 'concept' for an atmospheric profiler to be used in conjunction with the Next Generation Adaptive Optics (NGAO) system at Keck observatory. A brief overview of the available technologies for optical measurement of atmospheric turbulence is given followed by selection of an appropriate system for NGAO. A MASS/DIMM system is chosen as the best system that can meet NGAO requirements. This work was part of the system design phase of NGAO, a standard phase of new instrument development at W. M. Keck Observatory.

## 1. Introduction

The strength and location of atmospheric turbulence determines the ultimate performance of an adaptive optics (AO) system to study astronomical objects. More formally when the atmosphere is assumed to follow Kolmogorov or von Karman statistics the optical effects of atmospheric turbulence can be described by the index of refraction structure function constant, $C_n^2$. Typically the atmosphere is vertically stratified into thin layers with homogenous turbulence; each layer can be described by a constant $C_n^2$. Variation between these layers can be described by a $C_n^2$ that is a function of altitude in the atmosphere and designated, $C_n^2(h)$, where, $h$, is the height above the observatory. An atmospheric profiler is able to measure this function from the location of the telescope up through the atmosphere. Another method to determine the turbulence profile is directly from the laser tomography system of NGAO. However, this assertion is presently not verified. In any case, the same information from a source independent of the NGAO system can be useful for the following reasons:

- Acceptance testing
- Diagnostic during observing
- Aid to planning observations
- Improve accuracy or speed up the convergence of the laser tomography algorithm
- Useful as an aid in estimating the AO PSF across the instrument field of view

Based on these considerations, a separate atmospheric profiler was determined to be a desired part of NGAO system. This task was added to the NGAO plan in April 2007 [1] and this report represents the conclusion of that study. The authors of KAON 481 [1] did not specify the scope of the atmospheric profiler study, which was determined later by the authors [2] of the atmospheric profiler work scope planning sheet. The authors of the planning sheet [2] defined the scope of the study as:

> "Define the tools needed to support routine monitoring of the turbulence as a function of height over the observatory ($C_n^2$ profile). Such tools might include an external MASS/DIMM monitor. Identify requirements to support real time atmospheric tomography by the NGAO system and PSF calibration of science data as a post observing data reduction task."

## 2. Requirements

The author of this report, in consultation with Don Gavel and Mathew Britton, determined the top level requirements for the atmospheric profiler for NGAO tomography and PSF estimation. This process was not a direct flow down from the NGAO performance budgets for tomography and PSF estimation, but rather a survey of the available technology for atmospheric profile measurement and what appeared to be reasonable approach for measuring this information with consideration to the constraints imposed by NGAO. The results of this process are given in the remainder of this section.

Atmospheric turbulence is a non-stationary random process as such the update rate for the atmospheric profiler should be as fast as possible. In addition, it should operate automatically throughout the night to provide updates as conditions change. The profiler must also have the ability to measure the turbulence from upper altitudes and turbulence at ground level distinctly. The measured a profile can be of relatively low vertical resolution: 6 measurements spaced between 1 km and 20 km would be satisfactory. Also the profiler must provide a reasonable level of accuracy for measured strength of the turbulence of the order 10% or better for total seeing (i.e. $r_0$). A small footprint system is desirable as it can be installed at an existing facility and should therefore have a relatively easy permitting process with the Office of Mauna Kea Management. The highest level requirements for the atmospheric profiler are:

- Measure atmospheric profile at low resolution in 6 or more altitude bins, between 1 km and 20 km altitude
- Measure the profile once every 2 minutes
- Measurement accuracy of 10% or better in $r_0$
- Operate automatically when conditions are suitable for operating the Keck telescope
- Small physical size

A complete list of atmospheric profiler requirements is given in Appendix A. The requirements will evolve during the various phases of NGAO design please consult the most current version of the NGAO functional requirements document for more up to date information.

## 3. Techniques for Turbulence Profile Measurement

Several methods have been used to measure atmospheric turbulence. We review them briefly and comment on their suitability for NGAO. One method of measuring atmospheric turbulence is direct measurement by temperature probes carried aloft by balloons. While this method provides high temporal and spatial resolution it suffers from the drawback that the balloon will drift away from its launch site and record the turbulence at locations other than the telescope where it was launched. In addition, it is not practical or cost effective to launch a new balloon every few minutes. Sonic Detection And Ranging (SODAR) provides turbulence measurements located at the observatory and with high enough temporal frequency to be useful for NGAO but these instruments are limited to measurements of only the ground layer turbulence, approximately the first 200 meters above the instrument.

Historically, the limitations mentioned above have lead to the development of several optical based methods using natural stars as sources to measure $C_n^2(h)$. The first of these [3] was SCIntillation Detection and Ranging (SCIDAR) and its generalization [4] to measure turbulence over the entire atmosphere. The SCIDAR technique uses correlation in the scintillation patterns of binary stars to measure both the strength and altitude of turbulence in the atmosphere. Typical SCIDAR systems measure the turbulence between 0 and 20 km above the telescope providing vertical resolution between 100-500 m. The resolution is dependent on the angular separation of the binary star used as a test source. While facility SCIDAR systems have been installed at the 1.8m Vatican Advanced Technology Telescope (VATT) on Mt. Graham [5] and 1.0-m Jacobus Kapteyn Telescope (JKT) on La Palma [6], these systems require a dedicated telescope of moderate size, ~1-2 m diameter, and so are less suitable for installation at Keck for NGAO.

Several drawbacks of SCIDAR have been overcome by the Multi-Aperture Scintillation Sensor (MASS) [7] that uses the scintillation pattern from a single star to measure the turbulence profile and can be installed on small telescopes with diameter of 30 cm or larger. These design choices were made to enable MASS to be used at remote locations for site testing the next generation of large telescopes. Since it measures the light from only a single star the vertical resolution is the same for all sources but it typically is an order of magnitude lower than SCIDAR. While the resolution of the MASS instrument is relatively low and a function of altitude, approximately 500m at low altitude increasing up to ~8 km at the top of the atmosphere turbulence around 30 km, the low altitude resolution of the MASS technique is sufficient for NGAO purposes. For example, Britton [8] has used MASS/DIMM data for PSF estimation with NGS AO data taken at Palomar.

One less desirable feature of a MASS is its insensitive to low altitude turbulence below about 500 m. To overcome this limitation the MASS system is installed on the same telescope with a Differential Image Motion Monitor (DIMM). The DIMM instrument [9] measures the cumulative effect of optical turbulence in the entire atmosphere (i.e. $r_0$ or 'seeing'). The difference between the MASS measurement and the DIMM measurement is attributable to ground layer turbulence from 0 to 500 meters altitude above the telescope. A study of the accuracy of the DIMM technique is given by A. Tokovinin and V. Kornilov in reference [10]. The TMT has used several MASS/DIMM units manufactured by Kornilov's research group. The experience of the TMT group with these instruments is reported by Schöck in reference [11]. Details of the statistical errors (precision) and systematic error (accuracy) of the TMT systems are given in references [12] for DIMM and reference [13] for the MASS. These errors are comparable to values given in reference [10]. A table of these errors is reproduced below.

**Table 1**: Accuracy of TMT MASS/DIMM reproduced from reference [12] for DIMM and reference [13] for the MASS

| Instrument | Relative Error (statistical errors) | Absolute Accuracy (systematic errors) | Comments |
|---|---|---|---|
| DIMM | | | |
| Seeing (arc seconds) | 0.02 | 0.02 | |
| MASS | | | |
| Free atmospheric seeing (arc seconds) | 0.05 | 0.05 | Dominated by lowest altitude layer precision |
| Individual layers seeing (arc seconds) | <0.1 | <0.1 | |
| Isoplanatic angle (arc seconds) | 0.01 | <0.2 | |

Although the SCIDAR and MASS techniques has been successful at measuring the turbulence profile, they both suffer from nonlinearity inherent in the relationship between turbulence structure in the atmosphere and the scintillation seen at the ground. Recently, a new technique that uses direct measurement of the wavefront phase with Shack-Hartmann wavefront sensors has been developed. The new technique measures the wavefront of each component of binary star and cross correlates the two wavefronts to infer the turbulence profile. This method is known as SLOpe Detection and Ranging (SLODAR). SLODAR [14] provides profiles of atmospheric turbulence with relatively high vertical resolution (200 m) over the first few kilometers of the atmosphere up to about 2 km above telescope. These systems are being developed to measure the lowest levels of turbulence in order to determine the best sites for ground layer adaptive optics systems. Such a SLODAR system is able to operate on relatively small telescopes, typically 0.3 meters, and could be compatible with installation at Keck. However NGAO laser tomography will be sensitive to turbulence at altitudes higher than 2 km. It would be possible to extend the altitude sensitivity of SLODAR by installing such a system on a larger telescope [15] with a diameter of order 1-3 m. However, this is not practical for NGAO. These techniques are still in the development stages and should be watched as the development of NGAO proceeds. A similar technique might be useful for inferring the atmospheric profile directly from NGAO LGS wavefront sensor measurements.

## 4. Atmospheric Profiler Chosen for NGAO

Based on our requirements a Tokovinin type MASS/DIMM unit would be a satisfactory choice for NGAO. These units are available from Cerro Tololo Inter-American Observatory (CTIO) and have been provided to Palomar Observatory, TMT, and the European Southern Observatory (ESO). The TMT site testing group has spent considerable effort in characterizing these instruments as discussed in references [11-13] and summarized in **Table 1**. The TMT systems were designed to be setup in remote location, they operate in an automatic fashion including nightly startup and shutdown with no operator intervention required. They have a relatively small physical footprint. A TMT MASS/DIMM could possibly be mounted on the roof between the Keck domes or on the platform on either side of the dome shutter. These locations are indicated in the photograph in Figure 1. Either location is likely to have some local seeing effects particular to that position and will report different seeing than at either of the Keck telescopes inside their domes. These ground layer effects can be calibrated by comparison of the DIMM seeing and the seeing measured at the telescope using a science camera or an AO system derived seeing ($r_0$) measurement. Presumably the high altitude turbulence would be the same above all proposed locations. If only the strength of high altitude layers is important then the MASS measurement might be sufficient.

Recently, a group composed of Mark Chun (IfA), Derrick Salmon (CFHT), Bob McLaren (IfA), and Steven Businger (University of Hawaii) have proposed to the Mauna Kea directors that a facility atmospheric profiler should be installed for the use of all observatories and the Mauna Kea Weather Center. The proposed system would have a MASS/DIMM instrument located between the Gemini and CFHT telescopes as show in Figure 1 and Figure 2. This site is about 600 meters away from the Keck facility; it is at about 60 meters higher. If this site were used for NGAO, the difference in ground layer turbulence between this site and the Keck telescopes would need to be calibrated by steps similar to those mentioned above for a MASS/DIMM located on the exterior of the Keck building.

## 5. Experience Using TMT Mauna Kea Site Testing MASS/DIMM

The Thirty Meter Telescope project has installed one of its MASS/DIMM units to evaluate Mauna Kea as a possible site. The TMT MASS/DIMM unit was installed to the north and west of the Keck telescope as a location designated 13 North (13 N). The TMT has allowed several of the NGAO team members and some astronomers to make use of this data for the purpose of supporting the NGAO design. Our experience and that of other users has been that the instrument can be accessed over the web, data is recorded automatically, and results are updated every few minutes during the night. When the system is up, it produces reasonably accurate data. One draw back is that the system was probably down for 25% percent of the time when one excludes poor weather conditions. This high down time appears to result form the long time interval between when the system actual goes down and when it is serviced by one of the Gemini staff from Hawaii or a member of the TMT team from Pasadena. If such a system were to be used for NGAO where it would need to be operational on a nightly basis then the design would need to be modified to greatly reduce the downtime. An identical CTIO MASS/DIMM installed at Palomar [16] is operational a much higher percentage of the time and has a down time closer to a few percent, mostly for regular maintenance. The MASS/DIMM unit is the same the TMT units at 13 N but the telescope and other systems are different. The TMT site testing team has reported [17] that most of the downtime associated with the 13 N north site is due to availability of personnel to service the facility and limited wintertime access to the telescope (road to 13 is dirt and not cleared regularly by snow plows).

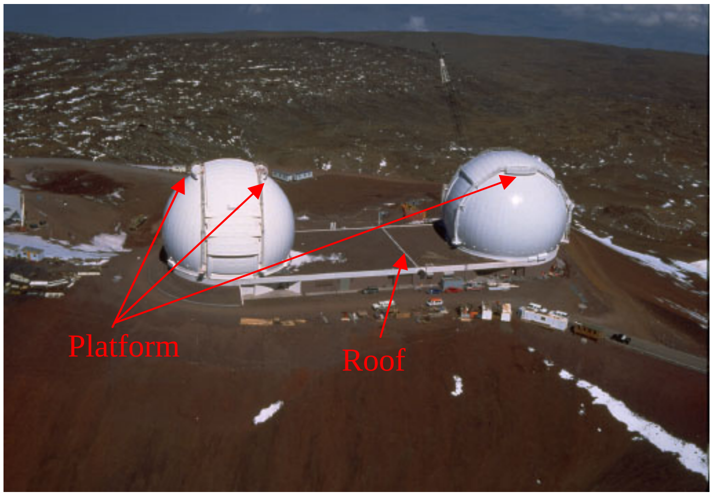


**Figure 1: Arial view of Keck Observatory with possible locations for atmospheric profiler indicated.**

**Figure 2: TMT seeing monitor superimposed on proposed site for Mauna Kea facility seeing monitor between Gemini (foreground) and CFHT.**

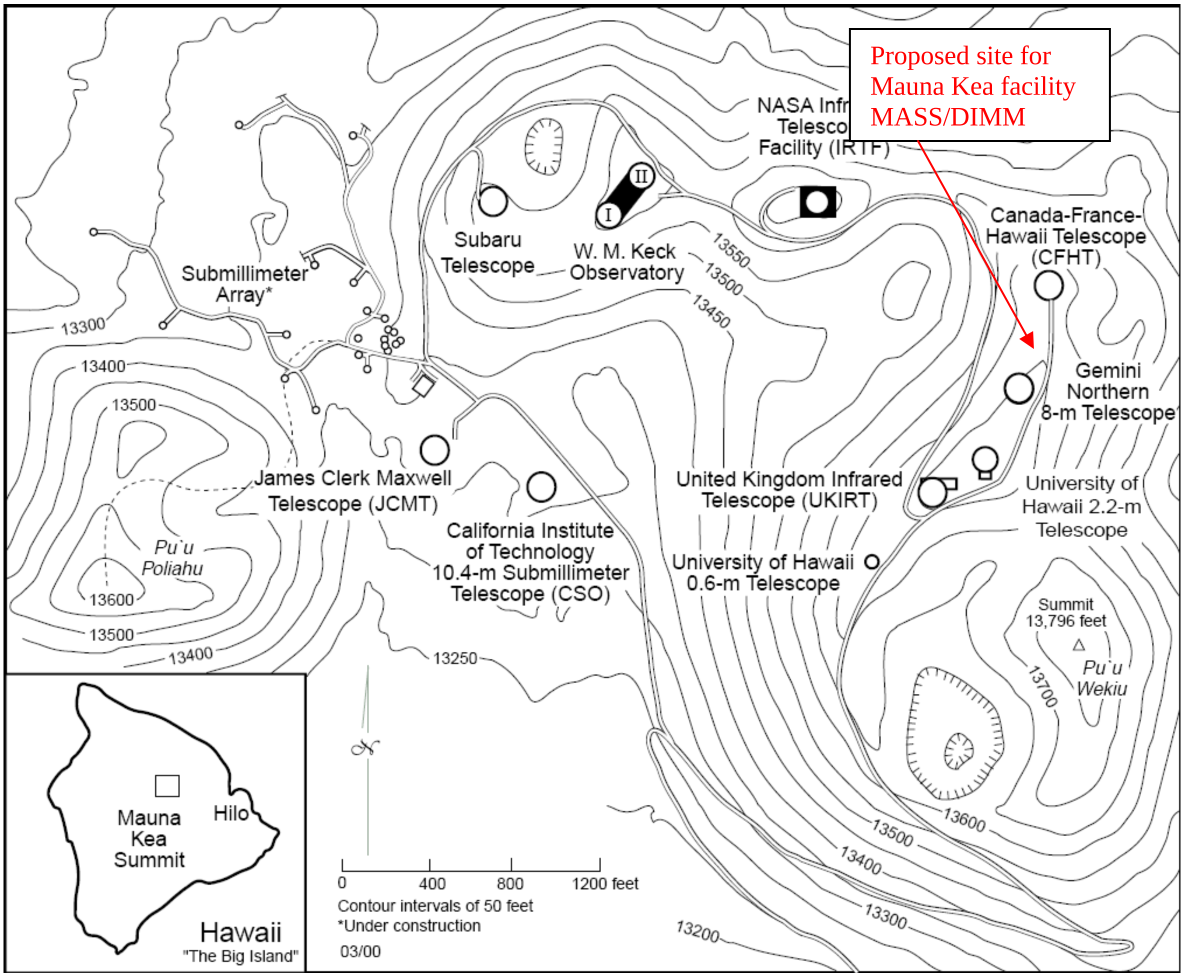


**Figure 3: Arial view of Mauna Kea showing the locations of the observatories and the proposed site for a facility atmospheric profiler.**

## 6. Risks

The major risks for the MASS/DIMM are the following. The risks are given a ranking on a consequence scale (5-server, 1-moderate) and a likelihood of occurrence scale (1-unlikely, 5-highly probable).

| # | Trend | Con-sequence | Like-lihood | Description | Status | Mitigation |
|---|---|---|---|---|---|---|
| 1 | | 1 | 3 | The need for the atmospheric profiler is not well defined. | See this report | 1) Determine if laser guide star wavefront measurements can provide $C_n^2$ profile during preliminary design |
| 2 | | 1 | 2 | Vertical resolution of MASS/DIMM may be too low | Estimated to be sufficient by Gavel and Britton | 1) Define $C_n^2$ profile errors impact for tomography<br>2) Define $C_n^2$ profile errors impact for PSF estimation |
| 3 | | 4 | 2 | Operational cost are high approaching 0.5 FTE | Estimate of support in Mauna Kea facility seeing monitor proposal | 1)Determine the cost of support for Palomar MASS/DIMM<br>2) Design MASS/DIMM for lower maintenance cost |
| 4 | | 5 | 1 | Uptime of MASS/DIMM is relatively low | Based on experience with 13 N MASS/DIMM system, see this report | 1) Issue is not intrinsic to MASS/DIMM units but other factors |

**Table 2: Risks for atmospheric profiler**

## 7. Recommendations

Based on our survey of atmospheric profiler technology, the author makes the following recommendations:

1) Use the Mauna Kea facility MASS/DIMM for NGAO.
2) If the Mauna Kea facility MASS/DIMM is delayed or canceled, install MASS/DIMM inside envelope of exiting Keck facility.
3) Determine utility and accuracy of dedicated atmospheric profiler for NGAO during preliminary design in particular evaluate utility of NGAO tomography based methods.

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**Appendix A: Requirements for Atmospheric profiler**

**Atmospheric profiler**
A monitor for atmospheric turbulence will be part of the NGAO system. The atmospheric profiler will use optical measurements of natural stars to infer the turbulence distribution with height over the telescope.

**Standard wavelength and zenith distance for reported data**
All atmospheric data will be reported at a wavelength of 0.5 microns and corrected for elevation effects to observation made at the zenith.

**Data products**
The atmospheric profiler will provide the following data products:

1) integrated seeing (units of arc seconds)
2) free atmospheric seeing (seeing at 500 meters and above) (units of arc seconds)
3) isoplanatic angle (units of arc seconds)
4) Fried parameter (units of cm)
5) layer integrated turbulence profile (units of m^$^{1/3}$)

**Greenwood frequency**
As a goal, provide an estimate of the optical turbulence layer velocities and the Greenwood frequency.

**Number of altitudes and resolution**
Provide a measure of the distribution of optical turbulence in altitude ($C_n^2(h)$ or the integrated value $C_n^2(h) \times \Delta h$ ) corrected to the zenith for at least six altitudes from 500 m to ~20km and with a spatial resolution of at least altitude/2.

**Accuracy**
The errors in the reported profile and integrated parameters will be as given in the following table:

| **Quantity** | **relative errors** | **absolute errors** | **Units** |
|---|---|---|---|
| Seeing | 0.02 | 0.02 | arc seconds |
| Free atmosphere seeing | 0.05 | 0.05 | arc seconds |
| Individual layers | < 0.1 | < 0.01 | arc seconds |
| Isoplanatic angle | < 0.01 | < 0.2 | arc seconds |

**Network interface**
The atmospheric profiler will provide a network interface to the Keck observatory local network.

**Interface to non real-time software**
The AO non real-time software will be able to report the pointing of the telescope to the profiler and request that it use the most appropriate (nearby) star. The AO control software will relay the profile data to the AO real-time control system (RTC) to assist in tomographic estimation. The AO software will also relay the profile information to the observatory data archive for use in AO PSF estimation.

**Duty cycle**
The turbulence profiler will update at 90 second intervals during normal operations.

**Use Mauna Kea facility seeing monitor**
If it meets all final requirements, with the exception of the requirement to be integrated inside the Keck observatory building, the facility Mauna Kea atmospheric profiler will be used for NGAO.

**Location**
The atmospheric profiler will be located as close as possible to the Keck telescopes. Tomography may be less dependent on accuracy of ground layer turbulence, allowing a relaxation of this requirement.

**Size**
The atmospheric profiler will occupy a space not greater than 3m by 3m by 3m in volume.

**Weight**
The weight of the atmospheric profiler will be less than TBD kg.

**Elevation**
The elevation of the atmospheric profiler will be as close as possible to the elevation of the Keck telescope primary mirror that hosts NGAO with a goal of 10 meters or less.

**Protected against inclement weather**
The turbulence profiler will be able to survive exposure to the exterior environment of the Mauna Kea summit or be enclosed in a dome or other structure that can open to provide access to the sky. If enclosed in a building, it must contribute minimal "local seeing" to the measurements reported by the atmospheric profiler.

**Operate at Mauna Kea summit**
The instrument must be able to operate in environmental conditions that exist at the Mauna Kea summit.

**Automatic operation**
The profiler will include the capability for automatic operation. This should include automatic startup and verification of status at start of a night. At the end of the night, the profiler will perform an orderly shutdown. The profiler will determine if high humidity or clouds are present, then enter a sleep mode of TBD minutes, after which time it will check to see if conditions have improved to allow operations. The profiler will provide diagnostics for data verification during operations. The profiler will warn the NGAO non real-time control software of bad data.

**Uptime**
The mean time between failure of the profiler will be such that if does not effect NGAO operations. Required mean time between failures is TBD.

**Maintenance**
The atmospheric profiler should be designed to minimize maintenance.

**Integrated into WM Keck summit facility**
If possible, the atmospheric profiler should be contained inside the footprint of the current W.M. Keck observatory facility.

**Time stamp data**
All data products will be time stamped to a precision better than 1 second. Time stamping should include the start and end of data collection for each sample.

**Archive calibration and processed data**
Archive calibration and processed data in a central archive, transfer data to NGAO data server.

**Continuous sky coverage**
The instrument will provide continuous sky coverage so that an estimate of r0 and atmospheric profile is possible whenever it is operating. Observations will be limited to zenith angles < 60 degrees.

**Startup and shutdown time**
Startup operations will take less than 5 minutes. Shutdown operations will take less than 5 minutes. The system can change to a weather-safe mode in less than 1 minute.

**Operation when telescopes operate**
Operate autonomously on Mauna Kea on nights when optical/IR telescopes are observing.

**Sensitivity**
The turbulence profiler will be able to operate when the atmospheric transparence is 0.90 magnitudes/airmass.