Design and Construction Status of the Daniel K. Inouye Solar Telescope

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1 Abstract

The 4m Daniel K. Inouye Solar Telescope (DKIST) will be the largest solar facility ever built. Designed to meet the needs of critical high resolution and high sensitivity spectral and polarimetric observations of the sun, this facility will support key experiments for the study of solar magnetism and its influence on the solar wind, flares, coronal mass ejections and variability in solar output. The design allows the facility to operate over a broad wavelength range (0.35 to 28 microns). The state-of-the-art adaptive optics system provides diffraction limited imaging and the ability to resolve features approximately 20 km on the Sun. Five first light instruments will be available at the start of operations: Visible Broadband Imager (VBI; National Solar Observatory), Visible SpectroPolarimeter (ViSP; High Altitude Observatory), Visible Tunable Filter (VTF; Kiepenheuer Institute, Germany), Diffraction Limited Near Infrared Spectropolarimeter (DL-NIRSP; University of Hawaii) and the Cryogenic Near Infrared Spectropolarimeter (Cryo-NIRSP; University of Hawaii). Site construction on Haleakala, HI began in December 2012 and is progressing on schedule. Operations are scheduled to begin in 2019. We provide an update on the development and construction of the facility and discuss plans for operations, including the DKIST Data Center development.

2 Introduction

The four-meter DKIST on Haleakala will be the most powerful solar telescope and the world's leading resource for studying solar magnetism that controls the solar wind, flares, coronal mass ejections and variability in the Sun's output[1]. The Sun is the most important astrophysical object to humanity. The magnetic heliosphere interacts with the earth's atmosphere impacting terrestrial climate and driving space weather, which can profoundly impact our planet's communications, civil infrastructure, economies and biology [2,3]. Because of its proximity, the sun can be studied at uniquely high resolution and sensitivity, providing a foundation and reference for stellar astrophysics. In particular, magnetic fields, which play an important role throughout the cosmos, can uniquely be studied on the sun. The sun serves as a laboratory for understanding plasma physics and the detailed interactions between magnetic fields and plasma over a large range of physical scales. To investigate, and ultimately understand and predict solar activity, we need to observe and model the physical processes throughout the solar atmosphere on their intrinsic spatial scales. The DKIST with its 4m aperture and a set of highly capable first light instruments offers unique capabilities for ground-breaking observations and quantitative analysis of solar magnetic fields. The large aperture DKIST and its powerful adaptive optics system will provide the spatial and temporal resolution to capture the highly dynamic processes involved in flares and coronal mass ejections (CME) that are amongst the main drivers of space weather [4]. In addition, the significantly increased resolution and the photon collecting area provided by the large aperture open up new discovery space, in particular, at so far relatively unexplored infrared wavelengths regimes. One of the most challenging goals of the ATST is to perform measurements of the coronal magnetic field. Two DKIST instruments are currently being constructed on Maui be the Institute of Astronomy will provide sensitivity and the spectro-polarimetric analysis tools that cover a wide temperature range and allow measurements of the illusive coronal magnetic fields [45. The high photon flux of DKIST is essential to accurately measure circular polarization (Stokes-V), which provides crucial diagnostics needed to distinguish magnetic configurations that lead to flares and CMEs from those that do not produce solar activity. Spectral diagnostic in the infrared is particularly attractive for coronal spectroscopy and magnetometry due to low sky and instrumental background and relatively bright mid-IR coronal emission lines.

There are many technical challenges involved in building a four meter solar telescope [6], including developing a high order adaptive optics system which operates at visible wavelengths and during challenging daytime seeing conditions, thermal control of facility and virtually all optical components, manufacturing the off-axis primary and the telescope mount structure that enables pointing and tracking with very high precision and accuracy.

This paper reviews the design, capabilities and construction status of the DKIST and its first light instruments, which can be operated individually or as a system and thus will provide a wealth of observational information that promises to significantly advance our knowledge of the sun and its magnetic field.

3 FACILITY OVERVIEW

Fig. 1 shows a rendering of the DKIST facility and its main subsystems. The main telescope is a 4m off-axis Gregorian design. The scientific and technical drivers for the off-axis design are discussed I a previous publication [7]. The optics is supported by the alt-azimuth telescope mount structure [8], which provides pointing and tracking.

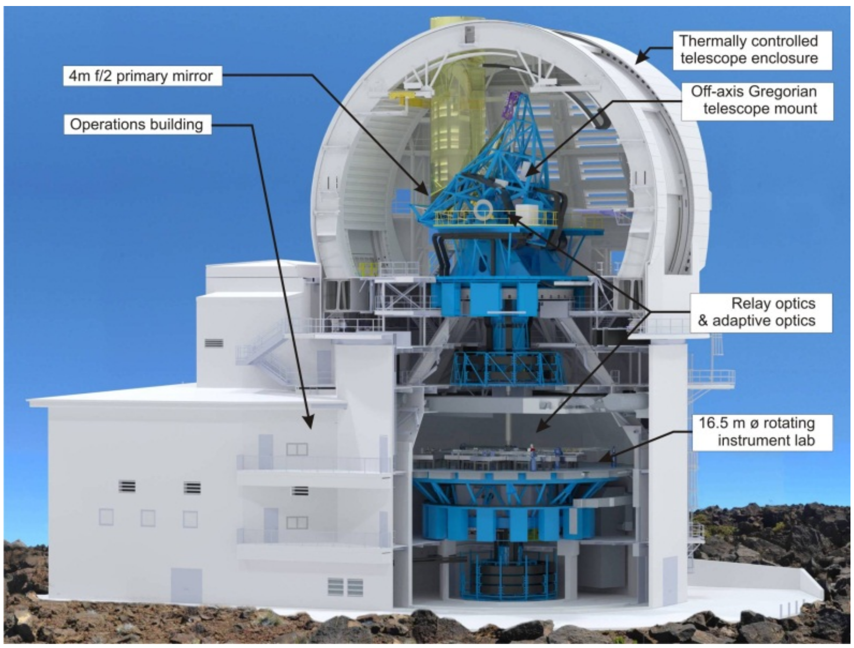

Fig. 1 Overview of DKIST facility and its major components.

The telescope is protected by a thermally controlled enclosure [9]. Transfer optics relays the light beam to the environmentally controlled coudé lab [10] where instruments are located on a rotating platform, which also serves as image de-rotator. The high order adaptive optics system[11] is integrated into the transfer optics and feeds four instruments that are designed to perform diffraction limited observations at visible and near infrared wavelengths and can operate simultaneously. Facility buildings include a support and operations building, the telescope pier [12], and the lower enclosure [13], which are directly attached to the telescope enclosure, and a detached utility building, which houses mechanical equipment, such as chillers, pumps, and air-handling units, and electrical equipment, such as a generator, and the main service feed. The support and operations building has three main floor levels with the telescope control room and an instrument lab at the same level as a rotating coudé platform inside the telescope pier.

Fig. 2 shows the entire optical path. The main mirror [14] is actively supported by 118 axial actuators. A heat stop in prime focus passes the 5 arcmin science field-of-view and rejects most of the 13kW solar heat load making thermal control of subsequent optical components a manageable problem. The 65 cm tip/tilt secondary is mounted on a hexapod and provides image motion compensation for the near limb coronal observations and future Nasmyth instruments. These components are grouped within the Top-End-Optical-Assembly (TEOA) [15]. The transfer optics include a number of flat and powered mirrors that direct the light to the instrumentation in the coude lab and form images of the entrance pupil on the 0.2m aperture fast tip/tilt mirror (M5) and the deformable mirror (M10) .

Fig. 2 DKIST optical path.

Minimization of seeing effects along the optical path is crucial to meet the challenging imaging error budgets, which flow from the top level imaging performance requirements. Both active and passive thermal control strategies are incorporated throughout the project. The Facility Thermal Control System [16] provides master control to the distributed elements in order to safely and economically monitor and operate the thermal equipment and control site power demand.

A key component of the DKIST is the waveform correction system, which enables the required diffraction limited observations at high Strehl at visible and infrared wavelengths [11]. The high order adaptive optics system is based on a correlating Shack-Hartmann sensor capable of locking on extended sources. The deformable mirror with 1600 actuators provides the high order correction that is expected to achieve a Strehl of 0.6 at visible wavelengths and during excellent seeing conditions.

Table 1 Summary design specifications.

Design Feature	Specification
Aperture	4 m (unblocked for low scattered light)
Field of View	2 arcminutes
Image quality	Diffraction limited (aO/AO systems) 0.03” (25 km) @ 500 nm
Spectral range	380 nm – 5000 nm (first light) 380 nm – 28000 nm (effective range)
Polarization accuracy	5×10^{-4}
Polarization sensitivity	10^{-5}
Lifetime	30+ years

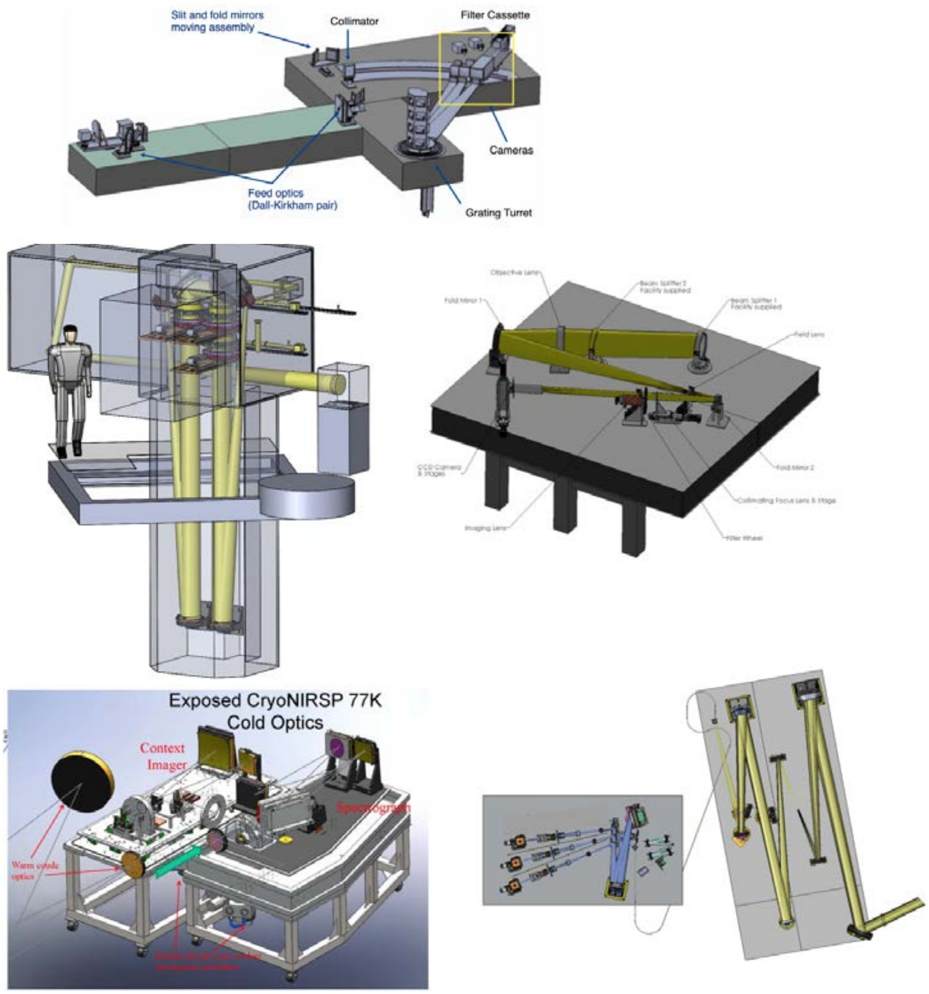

Fig. 3 First light instruments. Top left to bottom right: VISP, VTF, VBI, CRYO-NIRSP and DL-NIRSP.

4 FIRST LIGHT INSTRUMENTS

The five first light instruments (Fig. 4) are described in two recent publications [17,18] and consist of the Visible Broad-band Imager (VBI), the Visible Tunable Filter (VTF), the Visible Spectro-Polarimeter (ViSP), the Diffraction-Limited Near-Infrared Spectro-Polarimeter (DL-NIRSP) and the Cryogenic Near-Infrared Spectro Polarimeter (Cryo-NIRSP). The VBI and the VTF provide broadband and narrowband imaging while the ViSP and the NIRSP instruments are spectrograph based instruments. All instruments share a camera and data handling system provided by the facility. Polarimetry calibration and modulation are also functions of facility subsystems. The ATST instruments build on significant heritage of instruments operated at current facilities, such as the DST. The goal is to operate these instruments in Service Mode [19] for the majority of available observing time. The data collected by all instruments will be processed to remove instrument and residual atmospheric signatures (Level 1) at the NSO-ATST Data Center located at NSO Headquarters in Boulder. Distribution of data products for a broad user base is a function of the Data Center. The Science Working Group (SWG) is defining standard data products for each of the instrument that will be available to the community. This is done in the context of the Critical Science Plan which will be executed during the first two years of operations and will address the top priority science questions laid out in the Science Requirements Document and continuously updated and refined by the SWG.

Table 1 Summary of the high-level components with their contributing company/location and current status.

Component	Company	Location	Status
Telescope Mount Assembly	Ingersoll Tools	Rockford, IL	Coudé: Accepted Mount:Factory Testing
Enclosure	AEC IDOM	Bilbao, Spain	Accepted
Optical Systems: M1	Schott AG (blank) UofA COS (grind/polish)	Mainz, Germany Tucson, AZ	Accepted In Progress
Optical Systems: M1 Cell Assembly	AMOS	Liege, Belgium	Factory Testing
Optical Systems: M2 (Top End Optical Assembly)	L3	Pittsburgh, PA	Factory Testing
Optical Systems: M3, M4, M6 (Transfer Optics)	L3	Pittsburgh, PA	In Fabrication
Optical Systems: M5 (Wavefront Corr. Tip-Tilt)	Physik Instrumente	Auburn, MA	Accepted
Optical Systems: M7, M8, M9 (Coudé Optics)	TBD		Contracting
Optical Systems: M10 (Deformable Mirror Sys)	Xinetics	Devens, MA	Factory Testing
Optical Systems: Pol'n Calibration and Analysis	Meadowlark Optics (Pol'n Opt)	Frederick, CO	In Fabrication
Site: Excavation	Tom's Backhoe & Exc,	Kula, HI	Complete *
Site: Concrete	Reef, Rojac Trucking Inc	Wailuku, HI	Complete *
Site: Steel Erection	SteelTech Inc	Lahaina, HI	In Progress
Utility Building			Accepted
Support and Operations Building			In Progress
Site: Electrical	Du-Watts Electric Inc	Wailuku, HI	In Progress
Site: FTS/Plumbing	TBD	TBD	Planning
Instruments: Cryo-NIRSP	UH/IfA	Pukalani, HI	In Fabrication
Instruments: DL-NIRSP	UH/IfA	Pukalani, HI	CDR 2014
Instruments: VBI	National Solar Observ.	*	Lab Testing
Instruments: ViSP	High Altitude Observ.	Boulder, CO	CDR 2015
Instruments: VTF	Kiepenheuer Institute f. Solarp.	Freiburg, Germany	CDR 2015

5 CONSTRUCTION STATUS

The DKIST construction effort leading to first light has been organized into component systems which are integrated into a facility capable of meeting the challenging technical and scientific requirements [5]. Table 2 summarizes the status of these components as well as the companies and regions contributing to the final observatory. Overall, most major elements of the observatory are through final designs and into fabrication with several critical elements accepted.

5.1 Enclosure

The enclosure consists of the structure and mechanisms required to track and protect the telescope, providing a clear optical path to the Sun but preventing solar insolation outside the optical path, as well as supporting the thermal conditioning of the facility. The enclosure physical dimensions are: 72 ft [22 m] high and 87 ft [26.6m] in diameter. It will be erected on top of the Support and Operations Building lower enclosure which is at a height of 63.4 ft [19.3 m] for an overall facility height of 136 ft [41.4 m] (See [6] for details on the enclosure design). Unlike night-time facilities, the tracking of the enclosure and the solar aperture must be done with great precision. To facilitate a fast integration in the challenging environment at the summit of Haleakala, the enclosure was assembled at the IDOM factory in Hilfa, Spain and exercised through a range of performance verification tests to ensure compliance with all challenging controls and motion specifications. In particular, precise measurement throughout the structure was made to exhaustively explore the enclosure's response to wind, temperature changes and vibrations. All of these tests were successfully passed and the enclosure is currently being shipped to Maui in preparation for assembly in the fall of 2014.

Fig. 4 The enclosure assembled at the AEC-IDOM Hilfa facility, Bilbao Spain (February 2014).

5.2 Coudé Rotator and Mount

The Telescope Mount Assembly is composed of two major structures: 1) the Mount, 2) the Coudé Rotator. The platform is 16.5 meters in diameter and weighs approximately 115 tons. Given its size, mass and the criticality of maintaining a precise optical path to the instrument detectors, the Coudé Rotator has exacting requirements on its motion, and deviations from that motion (deflection and jitter) as it tracks a target. The Project awarded Ingersoll Tools, Inc the design and fabricate contract for the TMA. Again, with consideration of the challenges of integration on the summit, the Project opted to assemble and test the Coudé Rotator in the factory before installing at the site. Detailed factory testing has demonstrated that the Coudé Rotator meets all requirements and was accepted in June 2014 and is currently being shipped to Maui.

Fig. 5 Left: A picture of the Coudé Rotator in the Ingersoll, Inc. factory showing the dummy masses used to emulate the instrument loading. Right: The telescope mount structure with the two Nasmyth platforms and a partially assembled optical support structure.

Fig. 6 Left: The University of Arizona Optics lab showing (from front to back) the polishing support rig, stressed lap polishing head, the M1 blank in its box, and a commissioning blank (also produced by SCHOTT-AG) at the back of the room. Right: M1 cell assembly at AMOS in Begium.

5.3 M1 Blank and M1 Cell

As noted above, the science cases drive a need for high spatial and temporal resolution and sensitivity, both of which are achieved with a large mirror aperture. For a solar telescope, this imposes challenging thermal properties on the primary to ensure that the imaging characteristics are not degraded due to the heavy thermal load on the optic. SCHOTT-AG were awarded the M1 Blank contract and have produced an ATST 4.26m primary blank using ZERODUR glass-ceramic. This material has an exceptionally small coefficient of thermal expansion coupled with mechanical strength that will resist deformation; the blank has a thickness of only ~3 in (76 mm) to enable efficient cooling from behind but weighs approximately 3 tons. The produced blank meets or exceeds all of the critical geometric (shape including the machining of the asphere), thermal (coefficient of thermal expansion) and optical

(internal homogeneity, volume of inclusions) properties. The blank was accepted by the Project in January 2014 and has been received in Tucson, AZ by the University of Arizona's College of Optical Sciences; the UA COS team will perform the grinding and polishing on the M1 blank in preparation for coating and its operation. We expect this process to be concluded early in 2015.
The M1 mirror cell, which includes the active support and thermal control system is being manufactured at AMOS in Belgium and is approaching the factory acceptance testing phase.   The full assembly is expected on site in late 2015.

5.4 Top-End-Optical-Assembly

The TEOA consists of the heat stop in prime focus, the tip/tilt M2 assembly and a Lyot stop near a pupil plane located near the M2 [15]. L-3 Integrated Optical Systems Division has fabricated the 0.65-meter silicon carbide secondary mirror and support, including the mirror thermal management system and the mirror positioning and fast tip-tilt system shown in Fig.7 . The prime focus field stop and heat stop also build by L-3currently is undergoing factory testing utilizing a 10 kW laser to simulate the solar heat load.

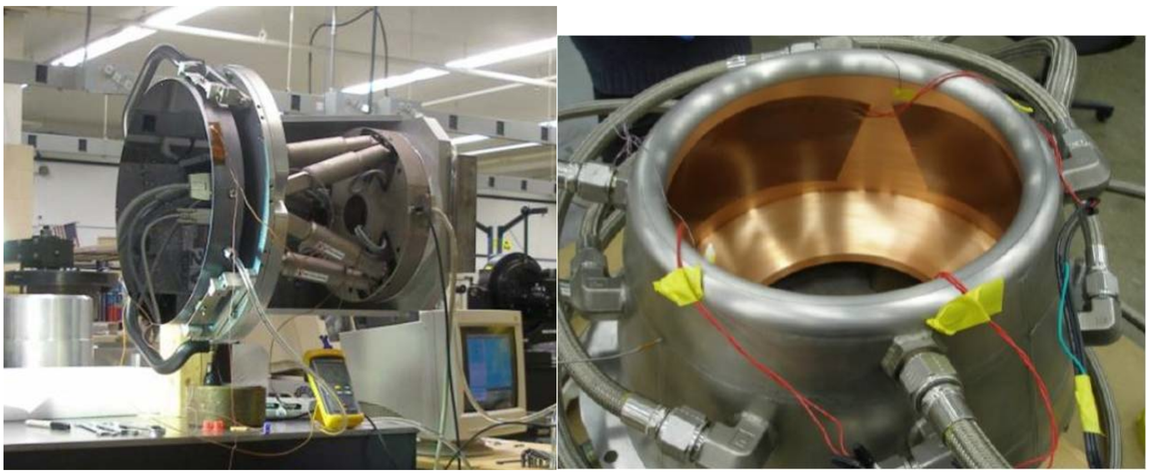

Fig. 7 Left: Tip/Tilt secondary mirror. Right: Prime focus heat stop.

5.5 Wavefront Correction System

The ATST has several correctors and sensors for wavefront correction[11]. The subsystems of the ATST wavefront correction system includes adaptive optics, which corrects atmospheric seeing at a minimum of 2 kHz update rates. The deformable mirror (DM) with 1600 actuators and a fast tip/tilt mirror provide high order correction and allow high Strehl imaging and spectroscopy even at visible wavelengths. The wave-front sensor is a correlating Shack Hartmann sensor with nearly 1400 sub-apertures. Post facto-image reconstruction is used, in particular, by the imaging instruments (VBI, VTF) to remove residual seeing effects and produce diffraction limited images and movies.
The main task of active optics is to correct slowly changing aberrations that may arise from gravitational and thermal deformations of the telescope structure and to keep the optical system aligned and the figure of the primary mirror within the allowed tolerances. The secondary mirror will also be used as an active element to correct focus and some higher order terms.
Fabrication and testing of key components is progressing on schedule. The fast-tip tilt mirror has been fabricated by Physik-Instrumented and has successfully completed testing. The fabrication of the DM is nearing completion and the wavefront sensor camera has been tested and integrated with the real time processing unit that performs the cross-correlations. Integration and testing will commence in the NSO labs in Boulder in August of 2015. Delivery to the Haleakala summit is scheduled for late 2017.

Fig. 8 The deformable mirror actuator array during assembly at Xinetics.

6 CONSTRUCTION SCHEDULE

The ATST proposal passed its FDR in 2009 and received its first funding in January 2010, anticipating approximately an 8 year construction schedule. However, although construction formally started in January 2010, the project did not obtain all of the required permits for the start of site construction until November 2012 (nearly 3 years later). As a result, the unavoidably-serial progression of events on site (excavation, concrete foundations, concrete structures (telescope pier, coudé pier, lower enclosure), steel erection (enclosure, buildings, telescope mount assembly), optical system installation and integration, instrument installation and integration, science commissioning and verification) were delayed and a new baseline was developed and approved (NSF, NSB) in August of 2013. The current high level schedule is illustrated below, culminating in a start of operations for DKIST in July 2019.

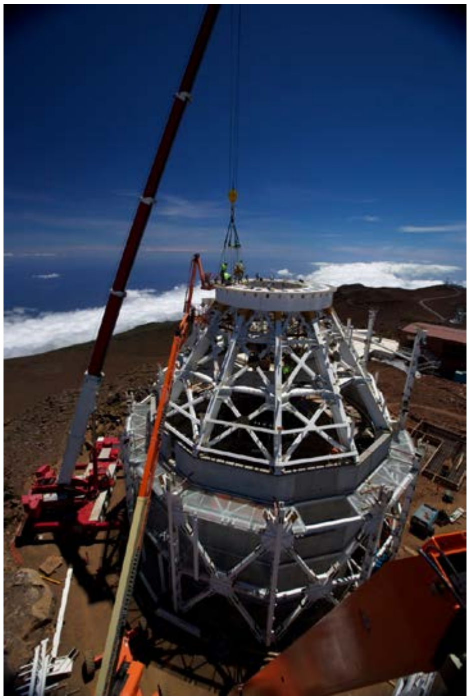

Fig. 9 Progress of site construction as of August 2014 showing the installation of the head ring on top of the pier cone [20].

7 SUMMARY

DKIST construction is progressing according to schedule and is expected to be fully operational in mid-2019. In spite of the many technical and logistical challenges the project is on track to become the world's premier resource for solar research. The Haleakala site is unique in that it provides excellent seeing and coronal sky conditions and thus supports high resolution disk observations as well as off-limb coronal observations, which require very low sky and instrumental background. The DKIST and its instrumentation are designed to take advantage of the excellent site conditions.

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