DKIST: Observing the Sun at High Resolution

A. Tritschler[1], T. R. Rimmele[2], S. Berukoff[2], R. Casini[4], S. C. Craig[3], D. F. Elmore[2], R. P. Hubbard[3], J. R. Kuhn[5], H. Lin[5], J. P. McMullin[3], K. P. Reardon[3], W. Schmidt[6], M. Warner[3], F. Wöger[2]

[1]*National Solar Observatory, 3010 Coronal Loop, Sunspot, NM, USA 88349*

[2]*National Solar Observatory, 3665 Discovery Drive, Boulder, CO, USA 80303*

[3]*National Solar Observatory, 950 N. Cherry Ave., Tucson, AZ, USA 85719*

[4]*National Center for Atmospheric Research, High Altitude Observatory, 3450 Mitchell Lane, Boulder, CO, USA 80307*

[5]*Institute for Astronomy, University of Hawai'i, 34 Ōhi'a Kū St., Pukalani, HI, USA 96768*

[6]*Kiepenheuer Institut für Sonnenphysik, Schöneckstrasse 6, 79104 Freiburg im Breisgau, Germany*

Abstract. The 4-m aperture Daniel K. Inouye Solar Telescope (DKIST) formerly known as the Advanced Technology Solar Telescope (ATST) and currently under construction on Haleakalā (Maui, Hawai'i) will be the largest solar ground-based telescope and leading resource for studying the dynamic Sun and its phenomena at high spatial, spectral and temporal resolution. Accurate and sensitive polarimetric observations at high-spatial resolution throughout the solar atmosphere including the corona is a high priority and a major science driver. As such the DKIST will offer a combination of state-of-the-art instruments with imaging and/or spectropolarimetric capabilities covering a broad wavelength range. This first-light instrumentation suite will include: a Visible Broadband Imager (VBI) for high-spatial and -temporal resolution imaging of the solar atmosphere; a Visible Spectro-Polarimeter (ViSP) for sensitive and accurate multi-line spectropolarimetry; a double Fabry-Pérot based Visible Tunable Filter (VTF) for high-spatial resolution spectropolarimetry; a fiber-fed 2D Diffraction-Limited Near Infra-Red Spectro-Polarimeter (DL-NIRSP); and a Cryogenic Near Infra-Red Spectro-Polarimeter (Cryo-NIRSP) for coronal magnetic field measurements and on-disk observations of e.g.

the CO lines at 4.7 microns. We will provide a brief overview of the DKIST's unique capabilities to perform spectroscopic and spectropolarimetric measurements of the solar atmosphere using its first-light instrumentation suite, the status of the construction project, and how facility and data access is provided to the US and international community.

1. Introduction

The Daniel K. Inouye Solar Telescope (DKIST)[1] is a 4-m open aperture all reflective telescope currently built on Haleakalā, Maui (Hawai'i). By 2019 when scheduled to move from commissioning into operations, the DKIST will be the largest solar ground-based resource for high-resolution studies of the Sun's magnetic activity leading to sunspots, flares, coronal mass ejections (CMEs), the solar wind and solar variability (Rimmele & ATST Team 2008; Rimmele et al. 2010, 2012). Polarimetric accuracy and sensitivity (5×10^{-4} and 10^{-5}, respectively), at high-spatial resolution on the disk, and far into the solar atmosphere (corona) is a high priority. Achieving this requires broad wavelength coverage far into the Infrared, where magnetic sensitivity can be orders of magnitude greater than in the visible. These challenging needs are reflected in the first-light instrumentation suite which combines instruments with imaging and/or spectropolarimetric capabilities operating at different wavelength ranges of the solar spectrum. In conjunction with the active optics and a high-order adaptive optics system this will allow the DKIST to obtain observations that can address a variety of scientific questions.

The DKIST will enable photospheric high-spatial resolution measurements of the ubiquitous quiet-Sun magnetic fields using Hanle and Zeeman diagnostics to study the magnetic field distribution and the effects of a local (turbulent) dynamo. Observations of sunspots and the fine-structure within will provide information about magneto-convective processes down to unreached spatial scales.

Spectroscopic and spectropolarimetric measurements probing chromospheric layers will allow to address important questions related to spicule and fibril physics, the three-dimensional thermal, magnetic and flow structure of and around sunspots and filaments.

Polarimetric measurements in combination with the fast imaging capabilities of some of the DKIST's instruments will advance our knowledge about the magnetic field before and after, the precursor activity, and the spatial, temporal and height scales related to solar flares.

The telescopes 4-m aperture, combined with an off-axis all-reflective design from a dark coronal site is essential specifically for observations of the solar corona. The DKIST will be able to probe the corona and its coupling to the chromosphere and photosphere shedding light on several fundamental coronal physics questions as e.g. the dynamics of the coronal magnetic field during filament and prominence eruptions, flaring and CME events, the prominence-cavity structure and its lifecycle, magnetic reconnection and MHD waves and their role in heating the corona.

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[1]The DKIST was renamed from the Advanced Technology Solar Telescope and dedicated to the late senator of Hawai'i Daniel Ken Inouye in December 2013.

Although nighttime operations are not envisioned, the DKIST could in principle provide opportunities for the planetary and stellar community to perform high-resolution spectroscopy over a wide wavelength range targeting stars and planets. During daytime Sungrazing comets can be observed.

In close collaboration with its Science Working Group (SWG) in order to guarantee community involvement, the DKIST is developing a Critical Science Plan (CSP) outlining early science that the DKIST will concentrate on during the critical transition phase when moving from commissioning into operations and beyond. The DKIST will provide access to the US and international community through a proposal merit process offering service mode and access (PI) mode operations. A variety of data products from facility class instruments will be served to the community through NSO's DKIST Data Center in Boulder, Colorado.

2. Facility Infrastructure

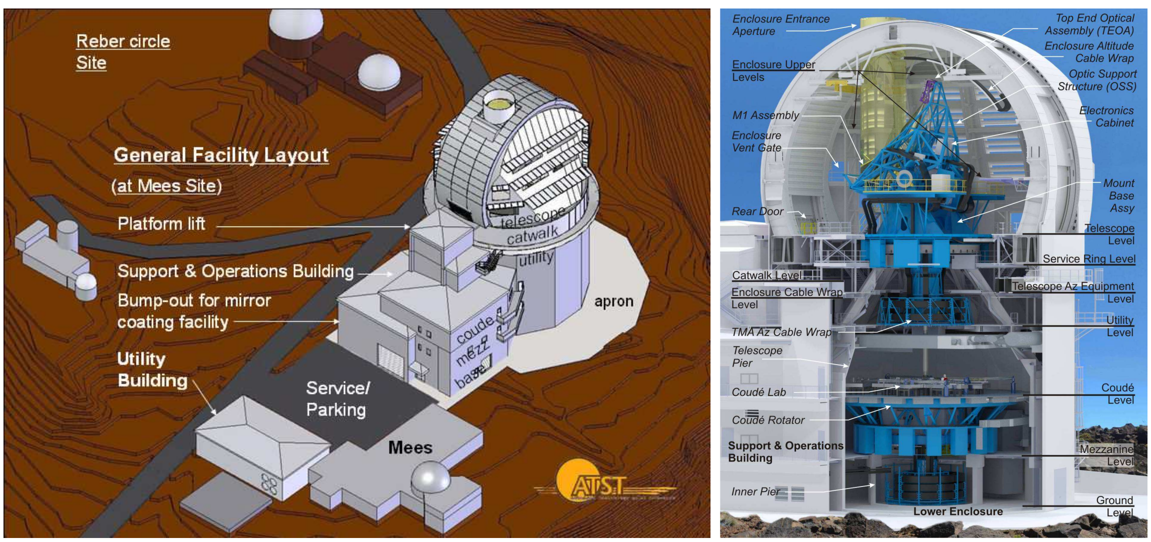

Figure .1: Left: Overview of the summit facility. Right: Telescope enclosure with details.

The summit facility (see Fig .1, *left*) involves the telescope upper and lower enclosure (see Fig .1, *right*), the support and operations building (S&O), and a detached utility building. The telescope upper and lower enclosure hosts the Telescope Mount Assembly (TMA) of which the most important parts are the telescope mount base structure and the optical support structure (OSS) (upper enclosure, see also Fig. .2, *left, top*) and the Coudé rotator (lower enclosure, see also Fig. .2, *left, bottom*). The support and operations building is a multi-story structure attached to the telescope building housing the control room, offices, instrument laboratory, mechanical equipment room and other support spaces that benefit from proximity to the telescope and Coudé instrument laboratory. The utility building is a two-story building located remotely from the telescope hosting equipment (mechanical and electrical) that, for reasons of heat and vibration, are required to be separated from the telescope and scientific instruments. A Remote Operations Building (ROB) located in

Pukalani (Maui) offering a Remote Operations Control Room (ROCR), office space and temporary data storage is currently in its design phase.

3. Telescope and Coudé Laboratory

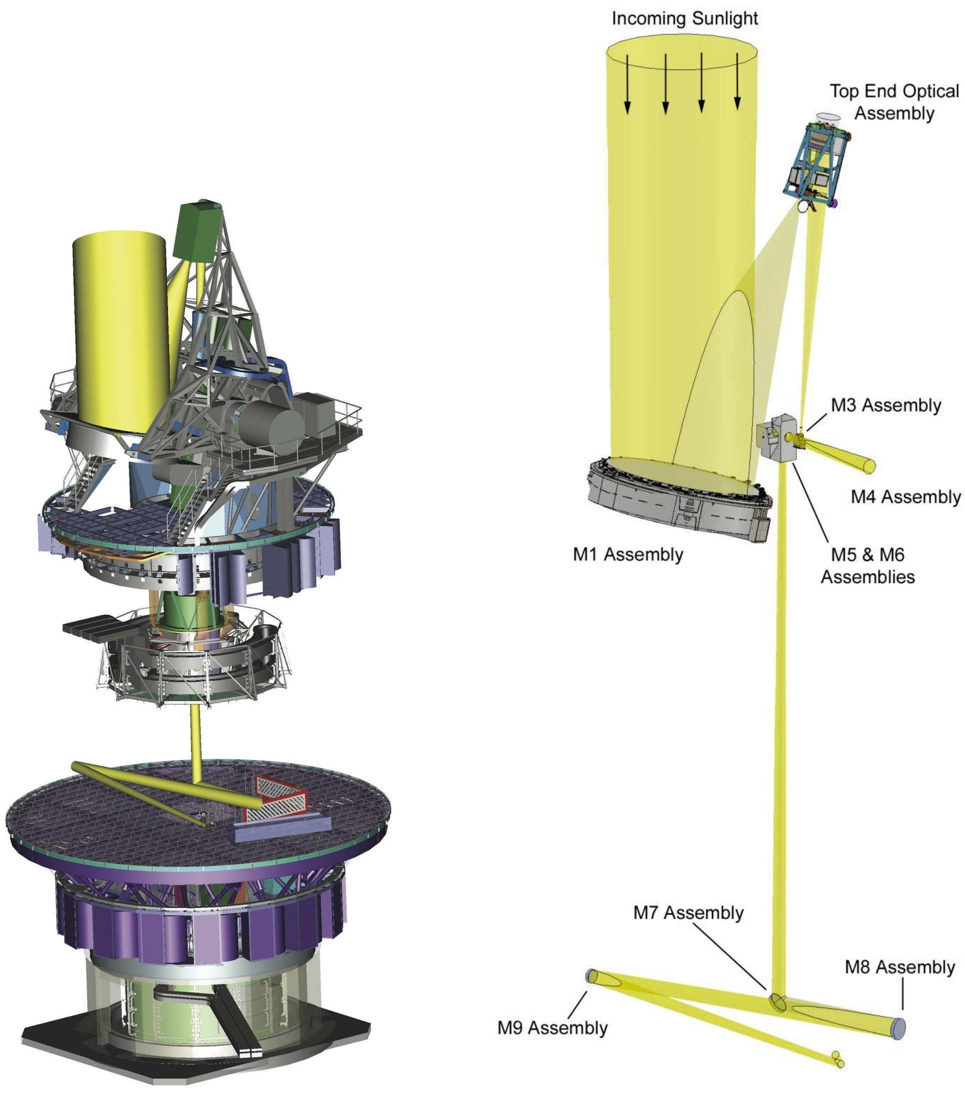

Figure .2: Left: Telescope mount assembly (TMA) with the telescope mount base structure and the optical support structure (top), and the Coudé rotator (bottom). Right: Optical path of the DKIST.

The DKIST is a 4-m clear aperture all-reflective off-axis Gregorian design with coronagraphic capability. The large-aperture will enable science at so far un-reached spatial scales resolving solar structures close to the diffraction limit (0.026 arcsec at 500 nm, 19 km on the

Sun). The primary mirror (M1, actively cooled) forms a $\sim$78 mm diameter solar image in the prime focus on the heat stop hosting a 5 arcminute circular aperture passing the light onto the secondary mirror (M2, mounted on a hexapod) forming an image in the Gregorian focus. The heat stop and the secondary mirror M2 are part of the Top-End Optical Assembly (TEOA). From the Gregorian focus eight additional mirrors (M3-M10, M10 is the deformable mirror) relay and direct the light into the environmentally controlled Coudé Laboratory where the light beam is distributed to the instrumentation using combinations of dichroic beam splitters. The off-axis optical design is obscuration-free aiding scattered light control and thermal control as the field-of-view (FOV) can be limited (5 arcmin) at prime focus. The all-reflective design allows exploitation of un-explored wavelengths in the Infrared up to 28 microns (not available for first light). An integrated active and adaptive optics system will provide a stable and high-order wavefront corrected light-beam (e.g. Rimmele et al. 2013) that is fed to most of the instruments in the Coudé laboratory. The adaptive optics systems and all instruments are mounted and fixed on a 16.25 m rotating platform (Coudé rotator) to compensate for image rotation introduced by the altitude-azimuth mounted telescope. The DKIST will also make available an integrated polarization analysis and calibration equipment located immediately above the Gregorian focus.

4. First-Light Facility Instrumentation Suite

The first-light instrumentation suite (Fig. .3) currently consists of five facility instruments covering a broad wavelength range of which four can be operated together ensuring science productivity and flexibility.

4.1 Visible Broadband Imager

The Visible Broadband Imager (VBI; Wöger et al. 2012) is a rapid imager utilizing broadband interference filters in the wavelength range 380-880 nm with passbands ranging from 0.05 nm to 0.6 nm mounted in turning filterwheels for high-spatial and -temporal resolution imaging of the solar atmosphere. The VBI takes raw data at frame rates up to 30 Hz and utilizes a quasi-real time speckle image reconstruction application to facilitate observations close to the diffraction limit of the DKIST with a 3 second cadence. The VBI has two spectral arms equipped with the following filters:

- VBI Blue: CaII K 393.3 nm, G-band 430.5 nm, blue continuum at 450.4 nm, Hβ 486.1 nm,
- VBI Red: Hα 656.3 nm, red continuum at 668.4 nm, TiO 705.8 nm,

and critical sampling of the diffraction limit at the shortest wavelength of each of the arms (0.011 arcseconds/pixel, 0.016 arcsecond/pixel). The FOV of the VBI blue and red is 45.2×45.2 arcsecond^2 and 69×69 arcsecond^2, respectively. The optical design allows for a full FOV of 2×2 arcmin^2 (squared) which can be acquired by a mosaicking capability. The VBI is developed by the NSO and is in fabrication and testing.

4.2 Visible Tunable Filter

The Visible Tunable Filter (VTF; Schmidt et al. 2014) is a tunable double Fabry-Pérot dual-beam spectropolarimeter working in the wavelength range 520-860 nm at frame rates up to

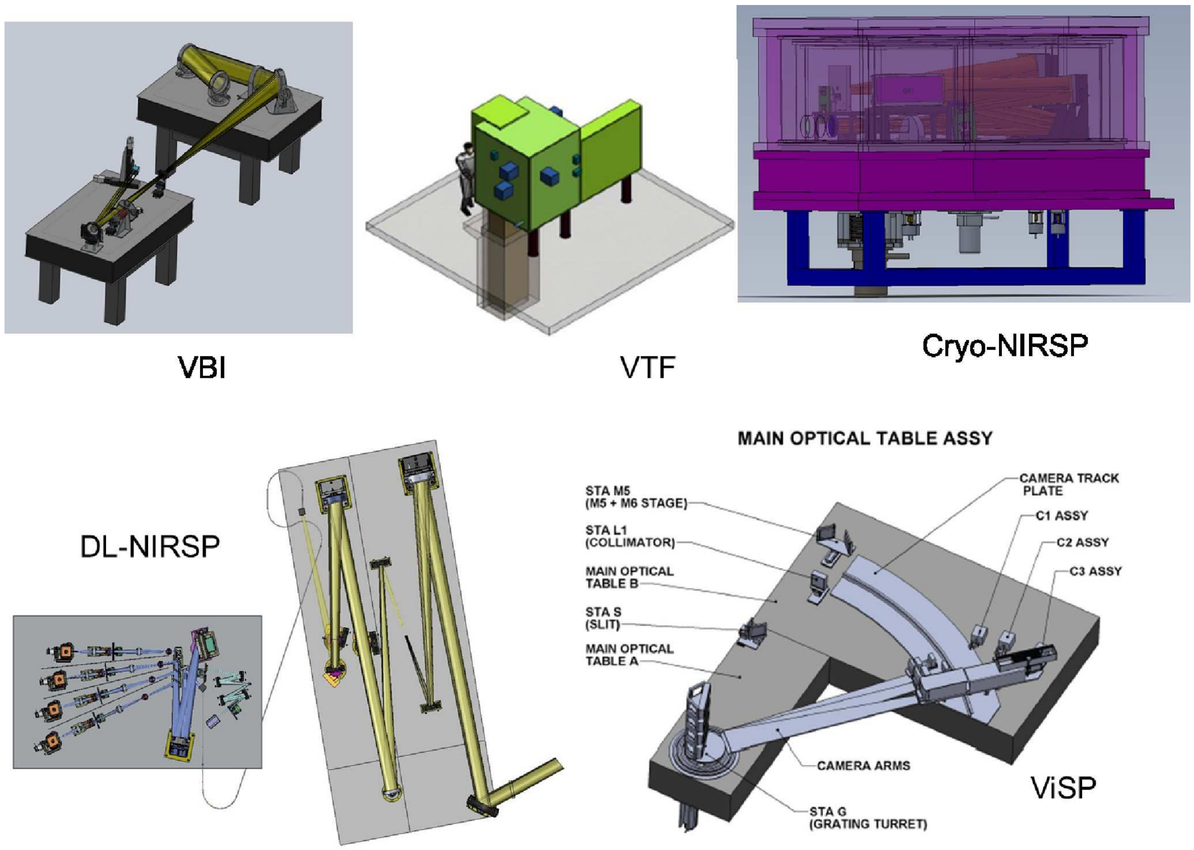

Figure .3: Rendering of the DKIST's first-light facility instrumentation suite.

30 Hz for high-spatial resolution spectroscopy and spectropolarimetry of the photosphere and chromosphere. The Fabry-Pérot etalons are in a telecentric mounting and allow for a circular FOV of 1 arcmin in diameter. The instrument has a spectral and spatial resolution of 6 pm at 600 nm and 0.03 arcsec at 500 nm, respectively. The VTF has two channels, of which one is the narroband tunable channel while the other one is a simultaneous broadband channel used for alignment, destretch and image reconstruction purposes. The VTF is being developed by the Kiepenheuer Institut für Sonnenphysik and is progressing through its Preliminary Design Phase.

4.3 Visible Spectro-Polarimeter

The Visible Spectro-Polarimeter (ViSP; de Wijn et al. 2012) is a single-slit dual-beam spectropolarimeter allowing to observe any spectral region in the wavelength range 380-900 nm to perform sensitive and accurate multi-line spectropolarimetry probing photospheric to chromospheric atmospheric layers. The ViSP uses an Echelle spectrograph and can be configured to use up to three spectral arms at the same time. The ViSP has a spectral resolution of 3.5 pm at 630 nm. The slit width can be chosen for 2× diffraction-limited spatial sampling at 450 nm, 650 nm, or 850 nm. The ViSP can sample 2 arcmin along its slit and up to 2.8 arcmin perpendicular to the slit by stepping the slit across the solar image. Depending on the required signal-to-noise ratio, the temporal resolution achieved can be 10 seconds or faster per slit position. The ViSP is developed by the High Altitude Observatory and is progressing through its Critical Design Phase.

4.4 Cryogenic Near Infra-Red Spectro-Polarimeter

The Cryogenic Near Infra-Red Spectro-Polarimeter (Cryo-NIRSP; Kuhn et al. 2012) is a cryogenically cooled single-slit dual-beam spectropolarimeter working in the wavelength range 1000-5000 nm at frame rates $\geq$ 10 Hz with a resolving power of 30,000-100,000. The instrument is designed to perform coronal magnetic field measurements and on-disk observations of e.g. the CO lines at 4.7 microns. The Cryo-NIRSP can sample 4 arcmin along its slit and up to 3 arcmin perpendicular to the slit by scanning the solar image in that direction with a 1 arcsecond spatial resolution at near- and thermal-infrared wavelengths. The instruments allows for on-disk observations close to 5 microns over a smaller 120×120 arcsecond^2 FOV with a higher spatial resolution (0.3 arcsec). The Cryo-NIRSP depends on the coronagraphic capabilities of the DKIST to observe both the near-limb (using DKISTs prime-focus and secondary occulting) and the more distant corona and heliosphere up to 1.5 solar radii. The instrument is mounted upfront the adaptive optics systems. The Cryo-NIRSP is being developed by the University of Hawai'i's Institute for Astronomy and is in fabrication.

4.5 Diffraction-Limited Near Infra-Red Spectro-Polarimeter

The Diffraction-Limited Near Infra-Red Spectro-Polarimeter (DL-NIRSP) is a fiber-fed two-dimensional dual-beam spectropolarimeter working in the wavelength range 900-2500 nm at frame rates $\geq$ 10 Hz with a resolving power of 50,000-200,000. The DL-NIRSP uses two different fiber-optic integral field units (IFU), of which one is designed for coronal observations (off-limb), while the other one is tailored to on-disk observations. The instruments full FOV (circular 2.8×2.8 arcmin^2) which is much larger than covered by the fiber arrays, can be accomplished through a field-scanning mirror. The DL-NIRSP can be configured using up to three spectral arms spanning approximately 500-900 nm, 900-1500 nm, and 1500-2500 nm each equipped with a set of dense wavelength division multiplexing (DWDM) band-pass filters isolating narrow spectral regions within that band. The DL-NIRSP is being developed by the University of Hawai'i's Institute for Astronomy and is progressing through its Critical Design Phase.

5. Construction

The DKIST is a Major Research Equipment and Facilities Construction (MREFC) project funded by the National Science Foundation (NSF) with the NSO as the Principal Investigator (PI) institution supported by four Co-PI institutions (i.e. High Altitude Observatory, New Jersey Institute of Technology Center for Solar Research, University of Hawaii Institute for Astronomy, and the University of Chicago Department of Astronomy and Astrophysics).

The DKIST has been organized into component systems which are then integrated into a facility which meets the scientific research needs. Currently, most of the major components are in fabrication or have been received by the project. For example, the major structures of the telescope mount assembly and enclosure have been fabricated and each has been fully assembled and tested in the factory, prior to shipment to the observatory site. The optical components are also in fabrication or acceptance testing with the exception of the Coudé

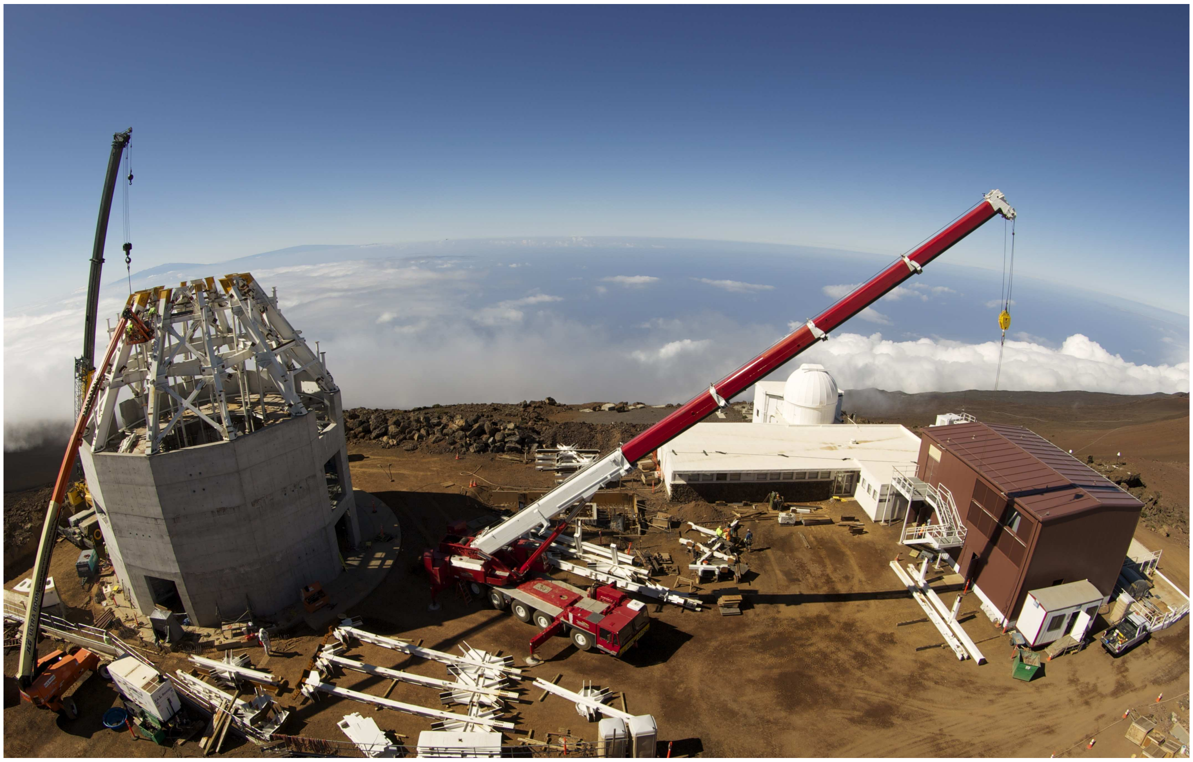

Figure .4: Construction site on Haleakalā, Maui, 21 May 2014. Left: Inner concrete telescope pier. Middle: Mees Observatory (white building). Right: Utility building

laboratory optics (M7-M9) which will be contracted out at the end of 2014. The 4.26 m M1 blank (ZERODUR glass-ceramic) was accepted by the DKIST project in January 2014 and is currently in the polishing phase at the University of Arizona's College of Optical Sciences mirror laboratory and is scheduled to be complete in the first quarter of 2015. The remaining areas in design are the first light instruments (Sect. 4.) and the wavefront correction (WFC) system. The instruments are currently passing through their critical design reviews, with all designs complete by mid-2015. Two of the instruments (VBI and Cryo-NIRSP) are currently in fabrication (Sect. 4.). The WFC system will conclude its final design review in early 2015.

Although the DKIST was initially funded in 2010 the permitting process for site construction took an additional two years, concluding in December 2012. Figure .4 gives an overview of the construction site on Haleakalā, Maui, as of 21 May 2014. The DKIST has an approximately seven year site construction schedule, working through the critical path development of:

– Site preparation, excavation and foundations.

– Lower enclosure.

– Enclosure erection.

– Telescope mount assembly (TMA).

– Optical systems installation and integration.

– Instrument system commissioning.

Currently, the project is nearing completion on the first two phases with a planned start to the enclosure erection in the last quarter of 2014. The enclosure erection will take approximately 1.5 years to complete. At this stage, the activities are focused on assembly, integration and verification of the various facility systems and the commissioning of the science instruments. The start of operations is scheduled for 2019.

6. Operations and Data Center

The DKIST will be operated more efficiently as current NSO facilities building on the experience gained in night-time and radio-astronomy, and the lessons learned from space-craft missions (e.g. Hinode, SDO, IRIS) and Service Mode Operations performed at NSO's Dunn Solar Telescope (DST). It is therefore and to maximize the high-impact scientific output, that in addition to the traditional model of allocating observing time during which a Principal Investigator (PI) has exclusive access to the telescope for a scheduled block of time (PI-mode, classical mode), the NSO will implement a *service mode*.

The service mode provides flexible assisted observing where the observatory staff operates the telescope, instruments and the associated support systems. Service time is not scheduled in blocks but allocated dynamically, i.e. the observatory staff (resident astronomers) on a daily basis decides what approved proposals (experiments) out of a daily priority list are executed and what instruments are operated. The service mode allows making efficient use of solar target availability, weather conditions and technical readiness and supports a broad range of different programs. Particularly, this mode is amenable to target of opportunity observations, can be used to perform (long-term) synoptic programs, and does allow for joint/coordinated (campaign) programs or other programs where special time constraints are given (e.g., rocket launch, balloon or space experiment). It is envisioned that scientific operations will be performed in service mode during a significant fraction of the available observing time.

The DKIST will also offer the more traditional *access mode* providing assisted observing when real-time or very close interactions with the Principal Investigator (PI) are necessary and special time constraints are given. In addition to scientific applications, the access mode is necessary to provide an opportunity for working at the facility on instrument development, installation and upgrade, particularly when training of staff or students is involved, but also in case critical elements of the facility have to be disassembled and repaired or replaced, or maintenance and engineering tasks need to be performed, all precluding observations of any kind.

Service mode time and access mode time will be made available to the US and international community through a proposal merit process in order to assure high-impact scientific use of the facility and support operations specifically during service mode operations.

In order to enable broad science inquiries from the full solar community, the data from the facility instruments will be managed and processed by a distributed operational data center, with resources housed primarily at the NSO headquarters in Boulder, Colorado, but with additional components on Maui. The data center will be eventually capable of storing and processing hundreds of petabytes of data acquired by DKISTs instruments, curating it during its lifecycle, and making it publicly available to a broad community of users. However, with starting of operations it is expected that at a minimum calibrated data will be made available to the users. The data center tasks will comprised of several functions, including but not limited to:

- Data processing pipelines, i.e. hardware and software resources capable of semi-autonomously creating calibrated scientific data and evolving to support multiple higher-level data products;
- Petascale storage infrastructure, capable of ingesting and curating 8 PB per year of raw and processed data, as well as up to 10^9 metadata entries per year;
- Advanced networking infrastructure to achieve robust transfer of data from the telescope to the NSO headquarters, as well as allowing timely transfer of the large volumes of data requests to the end users;
- Efficient data discovery and search capabilities to allow users to both drill down to individual data sets of interest as well as gather statistical samples over extended time periods.
- Management of varied and rich metadata, including calibration information, telescope operational status logs, and observing characteristics, to enable robust science, optimize operational support, and provide for long-term data stewardship and scientific repeatability.

These functions are necessary to promote the DKISTs contribution as a world-class facility for its intended lifetime, push forward the frontiers of solar physics, and engender new generations of solar physicists.

7. Summary

The DKIST is the largest solar ground-based facility currently under construction The observatory is designed to meet the high-resolution demands of critical solar science. The 4-meter aperture facility will operate over a broad wavelength range (380-2800 nm, 380-5000 nm at first light), using state-of-the-art active and adaptive optics systems to provide imaging close to the diffraction limit of the telescope. A configurable and flexible suite of five first-light facility instruments allowing for multi-instrument operations will be available at the start of operations. A balance of service mode and access mode operations, granted via a proposal merit process, will ensure efficient operations and maximize high-impact scientific output while still nurturing instrument development and customized scientific facility use.

Acknowledgements. The DKIST is managed by the National Solar Observatory (NSO), which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under a cooperative agreement with the National Science Foundation (NSF). The DKIST represents a collaboration of 20 plus institutions, reflecting a broad segment of the solar physics community. The NSO is the Principal Investigator (PI) institution, and the co-PI institutions are the High Altitude

Observatory, New Jersey Institute of Technology Center for Solar Research, University of Hawaii Institute for Astronomy, and the University of Chicago Department of Astronomy and Astrophysics. The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation.

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