Construction of the Advanced Technology Solar Telescope


1 National Solar Observatory, Sunspot, New Mexico, USA
2 High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, USA
3 Institute for Astronomy, University of Hawaii, Pukalani, Maui, Hawaii, USA
4 New Jersey Institute of Technology, Center for Solar-Terrestrial Research, Newark, New Jersey, USA
5 Department of Physics, University of Chicago, Chicago, Illinois, USA

Abstract. The 4m Advance Technology Solar Telescope (ATST) will be the most powerful solar telescope and the world’s leading ground-based resource for studying solar magnetism that controls the solar wind, flares, coronal mass ejections and variability in the Sun’s output. The project has entered its construction phase. Major subsystems have been contracted. As its highest priority science driver ATST shall provide high resolution and high sensitivity observations of the dynamic solar magnetic fields throughout the solar atmosphere, including the corona at infrared wavelengths. With its 4m aperture, ATST will resolve features at $0.03''$ at visible wavelengths and obtain $0.1''$ resolution at the magnetically highly sensitive near infrared wavelengths. A high order adaptive optics system delivers a corrected beam to the initial set of state-of-the-art, facility class instrumentation located in the Coudé laboratory facility. The initial set of first generation instruments consists of five facility class instruments, including imagers and spectro-polarimeters. The high polarimetric sensitivity and accuracy required for measurements of the illusive solar magnetic fields place strong constraints on the polarization analysis and calibration. Development and construction of a four-meter solar telescope presents many technical challenges, including thermal control of the enclosure, telescope structure and optics and wavefront control. A brief overview of the science goals and observational requirements of the ATST will be given, followed by a summary of the design status of the telescope and its instrumentation, including design status of major subsystems, such as the telescope mount assembly, enclosure, mirror assemblies, and wavefront correction.

1. Introduction

The 4m Advance Technology Solar Telescope (ATST) will be the most powerful solar telescope and the world’s leading ground-based resource for studying solar magnetism that controls the solar wind, flares, coronal mass ejections and variability in the Sun’s output. The ATST will replace the aging existing national solar facilities. The strong scientific case for the ATST has been presented in previous publications (Rimmele
& the ATST Team 2008). The science drivers lead to a versatile ATST design that supports diffraction-limited imaging, spectroscopy and, in particular, magnetometry at visible and near- and far-infrared wavelengths, and infrared coronal observations near the limb of the sun (Rimmele et al. 2010). A main scientific objective of the ATST is to precisely measure the three-dimensional structure of the magnetic field that drives the variability and activity of the solar atmosphere. The energy released in solar flares and coronal mass ejections was previously stored in the magnetic field. The magnetic field is structured on very small spatial scales and understanding the underlying physics requires resolving the magnetic features at their fundamental scales of a few tens of km in the solar atmosphere. The large 4m aperture of the ATST, which represents a transformational improvement over existing solar telescope opens up a new parameter space and is an absolutely essential feature to resolve features at 0.′025 (20 km on the Sun) at visible wavelengths.

New technologies developed at existing NSO facilities such as high order adaptive optics (Rimmele & Marino 2011) system are deployed to deliver a corrected beam to the initial set of state-of-the-art, facility class instrumentation located in the Coudé lab facility. At near infrared wavelengths the HOAO will enable observations of high Strehl for a vast majority of the available clear time. Magnetically sensitive spectral lines in the infrared will be used to reveal and study in detail the elusive internetwork magnetic fields (Lites et al. 2008; Stenflo 2011a,b) that cover the entire solar disk. The impact and significance of these fields, which may contain more than 80-90% of the solar magnetic energy, for the solar dynamo (Lites 2011), heating of the upper solar atmosphere and irradiance variations is not yet understood. The ATST will provide high precision polarimetric measurements of these fields, sometimes referred to as hidden or dark magnetic energy, by using combined visible and infrared diagnostics enabled by the powerful and sophisticated ATST first generation instrumentation. The 4m aperture will for the first time provide sufficient spatial resolution at near infrared wavelengths (60 km at 1.6 micron), where spectral lines are found that can provide the critical sensitive diagnostics needed to precisely measure the properties of the weak internetwork fields. The science requirement for polarimetric sensitivity ($10^{-5}$ relative to intensity) and accuracy ($5 \times 10^{-4}$ relative to intensity) place strong constraints on the polarization analysis and calibration units making ATST a high precision magnetometer (Keil et al. 2011).

A large photon collecting area is an equally strong driver toward large aperture as is angular resolution. Observations of the chromosphere and, even more so, the faint corona are inherently photon starved. The solar atmosphere is structured on small spatial scales and is highly dynamic. Small structures evolve quickly, limiting the time during which the large number of photons required to achieve measurements of high sensitivity can be collected to just a few seconds. Measurements of the weak coronal magnetic fields (Lin et al. 2004; Liu & Lin 2008) are essential to understand the physics of, e.g., coronal mass ejections and aid space weather prediction efforts. Measurements of the coronal magnetic field are desperately needed to make progress but are also extremely difficult. The coronal intensity is only $10^{-5}$ to $10^{-6}$ of the disk intensity. The polarimetric signal ATST aims to detect is only $10^{-3}$ to $10^{-5}$ that of the coronal intensity. This means that contrast ratios are of the order of $10^{-8}$ to $10^{-11}$ and, thus, are not too different from what planet detection efforts are facing. The large collecting area and low scattered light properties of the ATST are essential to achieve the chromospheric and coronal science requirements. The magnetic sensitivity of the infrared lines used to measure coronal fields and the dark sky conditions in the infrared are important motiva-
Construction of the ATST

Figure 1. Synthetic spectral profiles of Fe i 5576 Å extracted from two positions marked with the same color code in the image of a section of a penumbra (color of coordinate system frame = color of box marking position). The two images show the original MHD simulated image and the same image convolved with the ATST point-spread-function (bottom image). The synthetic spectra were obtained from combining the MHD simulations (Rempel 2011) with radiative transfer calculations. The thick solid lines (blue, purple) show the original synthetic spectra while the gray lines show the same spectral profile extracted from images convolved with the PSF of the 4m ATST, 1.5m GREGOR and 0.76m DST, respectively. Current telescopes are not able to recover the complex spectral signature that is crucial for understanding structure and dynamics of penumbral fine structure. ATST will be able to resolve spatially and spectrally the smallest magnetic features seen in these state-of-the-art simulations.

A main driver for a large-aperture solar telescope is the need to detect and spatially resolve the fundamental astrophysical processes at their intrinsic scales throughout the solar atmosphere. Modern numerical simulations (e.g., Stein & Nordlund (2006); Cheung et al. (2010); Rempel (2011)) have suggested that crucial physical processes occur on spatial scales of tens of kilometers. Observed spectral and, in particular, Stokes profiles of small magnetic structures are severely distorted by telescope diffraction making the interpretation of low-resolution vector magnetograms of small-scale magnetic structures difficult to impossible. Resolving these scales is of utmost importance to be able to develop and test physical models and thus understand how the physics of the small scale magnetic fields drives the fundamental questions, such as what causes the variations of the solar radiative output, which impacts the terrestrial climate (Solanki et al. 2004). The Sun’s luminosity increases with solar activity. Since the smallest magnetic...
elements contribute to this flux excess (Wenzler et al. 2006), it is of particular importance to study and understand the physical properties of these dynamic structures. Even the most advanced and newest current solar telescopes, such as the 1.6m NST or the 1.5m Gregor, cannot fully resolve the spectroscopic signature of such scales because of their limited aperture size (see Figure 1).

Since start of construction in 2010 the project is following the Project Execution Plan established and reviewed at the NSF-conducted Final Design Review. Commencement of site construction on Haleakala is tied to the ”all permits in place” milestone. After completion of the Final EIS, a Record of Decision was signed by the Director of the NSF on December 3, 2009. The project then submitted an application for the Conservation District Use Permit (CDUP), as required by Hawaiian statute. The Hawai’i Board of Land and Natural Resources (BLNR) voted and approved the CDUP on December 2, 2010. A contested case was immediately filed. Site construction will begin immediately after the expected successful conclusion of the contested case in April 2012.

Construction contracts for the major sub-systems of the telescope and instrumentation systems (e.g., M1 blank and polishing, enclosure, Telescope Mount Assembly, M1 Assembly, instruments), have been awarded and are proceeding according to schedule. The following sections summarize the design of the ATST’s major subsystems and for each system discuss the current status and major milestone schedule.

2. ATST Design, Status and Milestones

2.0.1. Overview

The 4m aperture will deliver unprecedented spatial resolution. At visible wavelengths (500 nm) the diffraction limit that will be achieved with an integrated high order adaptive optics system is 0′′03 arcsec or 25 km on the solar surface. The all reflecting optical design was chosen to allow exploitation of currently under-utilized and largely unexplored wavelengths regions in the infrared. development of these new diagnostic tools promises potential for new discoveries.

An off-axis Gregorian optical design will be implemented for the main telescope. The Gregorian design allows to limit the FOV to the desired 5 arcmin at prime focus thus avoiding scattered light of downstream optical elements, in particular M2. This design also renders the thermal control problem of optical elements manageable. The off-axis design avoids scattered light due to spider diffraction present in the classical on-axis design, which is a strong driver when infrared coronal observations are performed. Equally strong drivers for the off-axis design are of technical nature. The heat stop at prime focus requires a significant coolant flow, which can be easily delivered to the heat stop in an off-axis design. Wind induced vibrations of the secondary mirror that can be a limiting factor for imaging and, in particular, AO performance can be avoided to a large extent because the off-axis design allows for a extremely stiff secondary mount structure. Solar AO which uses low contrast granulation as a wavefront sensing target is impacted severely by flat field problems of the wavefront sensor detector as they are introduced by the rotating image of the M2 support spider in an on-axis design.

Low scattered light coronal observations in the infrared are enabled by occulting performed at prime focus by the heat stop and, for near limb observations, by an additional occulting edge at Gregorian focus. A Lyot stop can be inserted at a pupil
image located near the M2. Clean optics, in particular M1, is a prerequisite for coronal observations. In-situ mirror washing of M1 is possible and enables dust control. Furthermore, the M1 can be re-coated relatively frequently at an on-site mirror coating facility located at the nearby AMOS facility.

The integrated polarization calibration and modulation equipment enables high-precision polarimetry (Elmore 2011). The ATST is designed to achieve a polarimetric accuracy of $5 \times 10^{-4} I_C$. Achieving high polarization sensitivity is again aided by the large photon flux provided by the 4m aperture. We note that as always trades have to be made between spatial, spectral and temporal resolution as well as polarimetric sensitivity in designing and optimizing an observation that addresses a particular scientific question.

ATST science productivity is ensured by the initial set of facility-class instruments, which are mounted on a rotating instrument platform. These instruments can be operated simultaneously in various multi-instrument configurations. The instruments cover a broad wavelengths range from the UV to the infrared.

### 2.1. Support Facilities

The design of the ATST facility is shown in Figure 2. The site layout, exterior appearance and overall dimensions of the ATST facility were established early in the environmental permitting process and have not changed significantly in the past several years. The facility buildings include a support and operations (S&O) building, the massive telescope pier, and the lower enclosure, which are directly attached to the telescope
enclosure, and a detached utility building on the opposite side of a service and parking area. The S&O Building has three main floor levels with the telescope control room and an instrument prep lab at the same level as a rotating Coudé platform inside the telescope pier. At the center of the S&O Building and adjacent to the enclosure is a 22-ton platform lift for conveying the primary mirror assembly and large instruments between levels.

The remote utility building houses mechanical equipment, such as chillers, pumps, and air-handling units, and electrical equipment, such as a generator, and the main service feed. Ice storage tanks, to reduce peak-hour energy demand, are located adjacent to the utility building. The location of all the support facilities takes into account prevailing wind directions to minimize thermal turbulence. The new coating facility at the Air Force observatory will provide aluminizing of the ATST primary mirror.

Daytime seeing contribution from the lower enclosure are effectively and passively minimized by utilizing the thermal inertia of concrete. This same strategy is applicable to the attached S&O building, the exterior walls of which are now proposed to be clad with 6-inch thick precast concrete panels.

A Professional Services Sub-award Contract was awarded to M3 Engineering and Technology Corporation to perform Architectural and Engineering Services for the design development of the Support Facilities. Construction drawings and specifications have been delivered to the project in early 2012 and have formed the basis of formal Requests for Proposal (RFQs) used to bid the support facilities site work, including above-ground pier, lower enclosure support structure, and the operations building. Following a Ground-breaking Ceremony site construction work is scheduled to commence in Spring of 2012. The Utility Building is scheduled to be completed in mid 2013. The Support & Operations Building is expected to be finished in early 2016.

### 2.1.1. Enclosure

The ATST enclosure is comprised of the structural components and mechanisms that are used to protect and track with the Telescope. The enclosure’s main functions include protection of the telescope and optics under all weather conditions expected at the site; pointing, tracking and slewing along with the telescope over its full required range of travel, while providing full shading of the telescope structure; and protection of the telescope structure from wind-induced vibration and mirror buffeting, while still allowing good flushing characteristics in and around the telescope structure and optics.

Unlike most night-time telescopes which typically utilize an oversized viewing aperture, for solar observing the enclosure must be precisely sized and its pointing controlled to provide a clear optical path to the sun, but prevent solar heat flux outside of the optical path. The enclosure also provides infrastructure to support Facility Thermal Systems components for thermal conditioning of the Enclosure external surface and interior volume. The design phases of the subcontract for the enclosure have completed; successful Preliminary and Final Design Reviews were held in April 2011 and January 2012. Negotiations for the next phases of the work, procurement and fabrication of hardware and factory assembly and testing, are underway. Enclosure installation, integration and testing at the Observatory Site is envisioned for spring of 2014 through late 2015. The enclosure site fabrication, assembly and test will complete at the end of 2015.
2.1.2. **Telescope Mount Assembly**

The Telescope Mount Assembly (TMA) consists of the telescope mount and the Coudé rotator. The telescope mount supports and positions the M1 assembly and the transfer optics as the telescope tracks science targets on the sun. The telescope mount is significantly different to other large telescope mounts as it is an off-axis design so that the science beam is not vignette anywhere in its path by support structure. This fundamental design requirement means that although ATST has a 4m diameter primary, the telescope mount structure, bearings and drives are more similar to an 8m class telescope. The telescope mount which has a mass of approximately 200 tonnes will be able to point to anywhere in the sky within 5 arc-seconds prior to refinement based on image feedback. The Coudé rotator which is also part of the TMA supports the final four mirrors in the transfer optics and the suite of instruments on a 16m diameter platform. The Coudé rotator uses very similar technology to the azimuth drive and bearing system of the telescope mount but is capable of three times the velocity (6 deg/s) in order to improve observing efficiency. One of the novel technologies employed on the ATST TMA is the bearing system which comes from the machine tool industry and has been used extensively for machines of similar size and accuracy as the TMA.

The design-build contract for the TMA, which is under contract with Ingersoll Machine Tools in Rockford, IL, has successfully concluded ist Preliminary Design Review in Dec 2011. The detailed final design stage will process through to October 2012, at which point fabrication will commence. Fabrication will complete in fall of 2013. The TMA will be available for site assembly spring of 2015. TMA Mount installation is expected to be complete mid 2017.

2.1.3. **Facility Thermal Systems**

The Facility Thermal System is being designed under contract with AEC Idom. This work encompasses the design of the enclosure plate coil cooling subsystem, passive and active ventilation systems, and air scavenging and dehumidification systems. The preliminary design review for this work was successfully held and the completion of detailed construction documents is now in progress. The final design review is scheduled for June 2012.

A major subsystem is the Coudé Environmental System, which is the equipment and controls required to maintain an environmentally controlled (i.e., “clean”) laboratory space inside the Coudé lab. The design of this work is under contract with M3 Engineering along with the third major subsystem—the Facility Plant Equipment. This equipment includes heat recovery chillers, fluid coolers, ice storage tanks, and all the piping and pumps required to supply coolant to the support facility, enclosure, and telescope. The 95 complete review point was achieved in 2012.

Major milestones include the Facility Thermal Systems FDR in 2012, the Facility Management Systems fabrication, site assembly and test complete and the Facility Control System site assembly and test complete - both in 2015 - and the Facility Thermal Sub-systems fabrication, assembly and test complete in 2016.

2.1.4. **Telescope and Transfer Optical System**

The ATST optical system is also shown in Figure 3. For organizational purposes, the various optical elements have been divided into five subsystems based on function. In general, mirrors and pupils are grouped together if they move together as the telescope
Figure 3. The Telescope Mount Assembly (left). The telescope mount supports and positions the M1 and M2 assemblies, and the transfer optics as the telescope tracks science targets on the sun. The rotating instrument platform is part of the TMA. The Top-End-Optical-Assembly shown in detail on the right (green box in left image) is comprised of the fast tip-tilt M2, a hexapod positioner, the heat stop in prim focus and a Lyot stop in a pupil plane.

moves to track the sun and the Coudé room moves to de-rotate the image and align spectrograph slits in the preferred direction.

- Gregorian Optics - This subsystem includes the entrance aperture, M1, M2, the Lyot stop and the Gregorian focal plane where the Gregorian Optical Station (GOS) resides. The GOS houses the polarimetry calibration optics, modulators, calibration targets and calibration light sources. The optical elements, beam envelopes and the gut ray move with the Optical Support Structure (OSS).

- Coudé Transfer Optics - This subsystem includes M3 and M4, which combine to place the beam over the elevation axis. The optical elements, beam envelopes and the gut ray move with the OSS. This subsystem also includes M5 and M6 which combine to place the beam over the azimuth axis and directed towards the Coudé room. The pupil image located near M5 and M6 is used by M5 for fast tip-tilt control and M6 for the active optics bore-sight alignment function.
• Coudé Rotator Optics - This subsystem includes M7, M8, M9, M10, which combine to make a horizontal, collimated beam for introduction into the Coudé instrumentation distribution system. The deformable mirror (M10) of the high order adaptive optics system is located at a pupil image. The optical elements, beam envelopes and the gut ray move with the Coudé Rotator.

The primary mirror has been cast by Schott, Germany and will be shipped to the Optical Sciences Labs in Tucson Arizona for polishing to its final off-axis parabolic shape in Spring 2012. The M1 polishing effort is expected to conclude with delivery of the mirror to the Haleakala site in early 2014. The M1 cell assembly, which includes the active support and thermal control systems will have its FDR in 2012. Delivery to the site and integration of M1 mirror and M1 cell assembly. Integration of the M1 assembly with the telescope mount structure is a critical milestone that is expected to be achieved in fall of 2017.

The Top-End Optical Assembly, which includes the M2 and associated positioning systems, has successfully concluded its PDR. Major milestones are the completion of TEOA Acceptance testing scheduled for spring of 2015 and delivery of TEOA to site. Subsequently the integration with the telescope mount structure will commence in 2017. The Transfer optical elements are scheduled for integration in 2017. Upon completion the Coudé lab will receive first engineering light.

2.1.5. Wavefront Correction

The top-level science requirements that drive the ATST wavefront correction design are listed in the ATST Science Requirements Document. The ATST wavefront correction system is required to achieve the high Strehl requirements at visible and infrared wavelengths. The requirements are to achieve: a) Strehl $\geq 0.3$ for $r_0(500\, \text{m}) \geq 7\, \text{cm}$. This requirement defines the ATST imaging performance for seeing conditions for which the solar adaptive optics (AO) will function effectively. According to the ATST site survey data $r_0(500\, \text{nm}) \geq 7\, \text{cm}$ describes seeing conditions slightly better than median seeing at the Haleakala site. b) Strehl $\geq$ for $r_0(630\, \text{nm}) \geq 20\, \text{cm}$. This requirement defines the ATST imaging performance for excellent seeing conditions, during which high-priority science objectives will be achieved.

The ATST has several correctors and sensors for wavefront correction including active optics and high order adaptive optics. Active optics functions include keeping the entire optical path - most importantly M1 and M2 - aligned either by look-up tables or in closed-loop and keeping the figure of M1 within tolerances, compensating for deformation due to gravitational and thermal distortions. The secondary mirror will also be used as an active element of the aO to correct focus and coma terms. Information from different wavefront sensors will be processed by active optics control system in order to derive the appropriate drive signals for all corrector elements. The wavefront sensor information for aO will be derived from measuring wavefront errors averaged over hundreds of atmospheric realizations and thus provide information about slowly varying aberrations due to optical misalignment and/or M1 figure errors. FEA analysis and optical modeling shows that correction of up to 20 modes is sufficient for the M1. The aO controller updates the six rigid body degrees-of-freedom of the secondary mirror (M2), the figure shape of the primary mirror (M1), and the tilts of two mirrors (M3 and M6) that maintain the image and pupil boresight of the optical beam in the Coudé lab.
Fast tip/tilt devices (M2 and M5) are used for image stabilization. M2 is used to stabilize the image of the solar limb onto an occulting device placed at Gregorian focus. The limb occulter will enable low-scattered light observations of near limb features such as spicules and prominences. High-order adaptive optics is deployed for correcting atmospheric and internal seeing, and residual optical aberrations. The HOAO, which corrects atmospheric seeing at a minimum servo loop update rate of 2 kHz, is the most complex subsystem of WFC. The system has a 1933-actuator Deformable Mirror (DM) and a fast tip/tilt mirror. Both mirrors are integrated into the transfer optics that feeds light to the instruments. The wave-front sensor is a correlating Shack Hartmann sensor with 1737 subapertures.

We note that development of the Nasmyth instrument station is not within the scope of the construction project. Nevertheless, Nasmyth instruments, including wave-front correction equipment, are envisioned to be developed and commissioned during the early operations phase. Similarly, the optical design of the transfer optics allows for an upgrade of the conventional AO to multi-conjugate AO.

The thermally controlled DM and wavefront sensor systems for the high-order adaptive optics and active optics will be located in the Coudé lab. Both devices currently under contract and will be delivered to the project in 2012 (M5) and 2014 (DM, M10). Design and development of the real time processing system based on FPGA technology is also progressing with a combination of industry contracts and in-house effort. The large format, high-frame-rate wavefront sensor camera has been delivered and has passed acceptance testing. Commissioning of wavefront correction systems at the Haleakala site is scheduled to begin in early 2018.

2.1.6. Software systems

The Observatory Control System, Instrument Control System, and the Data Handling System are under construction and beginning to meet the major requirements of their respective first releases. Design work has begun on the Virtual Camera Controller. The Telescope Control System (TCS) is under contract, along with the software development of the enclosure control system. A TCS Simulator is now available and delivery of the TCS is scheduled for early 2013. Contracts for the software control of the telescope mount assembly, M1 assembly, and Top End Optical Assembly have been issues and work is progressing according to the schedule of the respective subsystem. The construction-ready version of the Common Services Framework was released.

2.2. Facility Instruments

The initial set of facility instrumentation, shown in Figure 6, includes the Visible Broad-band Imager (VBI), the Visible Spectropolarimeter (ViSP), the Diffraction Limited Near-Infrared Spectropolarimeter (DL-NIRSP), the Cryogenic Near-Infrared Spectropolarimeter (Cryo-NIRSP), and the Visible Tunable Filter (VTF). All instrumentation is located at Coudé. Instruments that are envisioned to be added shortly after first-light include a Near-IR Tunable Filter. Visitor instruments can also be accommodated on the Coudé platform. One of the attractive aspects of ATST is the requirement for simultaneous observations with several of these instruments and when combined with diffraction limited imaging, offers a significant advance in capability to the solar community. This kind of diversity and flexibility of post-focus instrumentation is crucial for modern solar research.
Figure 4 shows the Coudé lab instrument layout. Different combinations of mirrors and/or dichroic beam-splitters will be used to distribute the light to the various instruments. The VBI has passed its CDR and has progressed into the construction phase. The ViSP, DL-NIRSP and Cryo-NIRSP have all passed PDR and have now entered the critical design phase, which will be concluded in approximately one year from now with a CDR.

To accommodate the science requirement for a flexible, adaptable facility that can be quickly configured for a variety of diverse experiments, provide long-term support and maintenance of facility instruments, and to accomplish this in a cost-effective manner, the ATST project has adopted a strategy that calls for a high level of standardization in our approach to instrumentation. The light feed for all instruments, except for the Cryo-NIRSP, which is primarily a coronal instrument, includes the high order adaptive optics system. A common data acquisition and handling system will be used to collect, pre-process, and display data from all instruments. The polarization calibration system is common to all instruments, spectrographs and narrow-band filter systems. Polarization modulator are optimized for each instrument and, with the exception of the Cryo-NIRSP, are located within each instrument. However, hardware and software to control modulators will be provided and supported by the project. The project has specified and supports hardware and software for a standard motion controller. By adopting these standards, duplication of effort will be avoided in the areas of polarization modulation and calibration, camera control, data storage and display, and mechanism control.

2.2.1. Visual Broadband Imager (VBI)

The Visual Broadband Imager (VBI) is designed to provide diffraction limited images and movies at a number of wavelengths that image the photosphere and the chromospheres. The VBI will reveal solar structure at unprecedented resolution and capture dynamical processes with high cadence imagery. The instrument is divided into two components that cover blue and red wavelengths regimes. The VBI red covers wavelengths in the range 650 nm-860 nm and for first light included includes interference filters for for Hα, TiO, and potentially a coronal emission line. The VBI blue covers
Figure 5. This image was acquired using the ATST VBI interference filter and the ATST baseline camera while undergoing acceptance testing at the Dunn Solar Telescope (DST). The image shows a sunspot in the “hydrogen beta” absorption line (486.1 nm). Due to its narrow passband (0.05 nm) this filter is pushing current optical technology to its limits. The solar structure seen in this image originates from heights in the solar atmosphere that span from the photosphere to the chromosphere. The filamentary chromospheric features are evolving on time scales of a few seconds and are still unresolved in this DST image, even though, application of DST high-order adaptive optics and post-processing techniques resulted in diffraction limited resolution. The insert reveals the full DST resolution, which is less than 1/5th the resolution that the ATST will deliver. ATST will fully resolve these magnetic structures that are the root cause of solar activity.

the wavelengths regime 390 nm-490 nm and includes Ca ii K, G-band, blue continuum, and Hβ imaging (see e.g. Figure 5). The FOV is 2′ × 2′. Each beam will feed a single 4K×4K detector. Pixel sampling will be according to the Nyquist criterion at 430 nm and 656 nm, respectively. A temporal cadence of 3 sec per reconstructed image will be achieved. The ATST team is currently constructing the VBI blue. Construction of VBI red is scheduled to commence in 2012.

The VBI, both red and blue, will take advantage of ATST’s high spatial resolution by using a combination of adaptive optics and post-facto image reconstruction Wöger & von der Lühe (2007). These techniques benefit from the enhanced signal-to-noise provided by the AO correction. The VBI will be required to record images at an extremely high rate and compute reconstructed images close to the telescope’s theoretical diffraction limit using a speckle interferometry algorithm in near real-time. The VBI’s high
data volume drives the requirements of the Data Handling System (DHS) (Wöger et al. 2010) in two ways. The VBI will generate two data streams of up to approximately one gigabyte per second each in order to meet the requirement of one reconstructed image per 3 seconds. Additionally, in order to compute a reconstruction with accurate photometric properties, this data stream has to be merged with HOAO telemetry data during the reconstruction process. A high powered GPU based processing unit is considered to implement the near real-time reconstruction pipeline.

2.2.2. Visible Spectro-Polarimeter (ViSP)

The ViSP (Nelson et al. 2010) will provide precision measurements of the full state of polarization (i.e., all four Stokes parameters $I, Q, U$, and $V$) simultaneously at diverse wavelengths in the visible spectrum, and fully resolving the spectral profiles of spectrum lines originating in the solar atmosphere. Such measurements provide quantitative diagnostics of the magnetic field vector as a function of height in the solar atmosphere, along with the associated variation of the thermodynamic properties. Furthermore, information about protons and electrons in flares can be deduced from analyzing the polarization of strong lines during flares.

This instrument provides high spatial and polarimetric resolution spectra with the capability of scanning a large field of view. Wavelength diversity is a key element of the instrument allowing the ViSP to simultaneously perform spectropolarimetric maps in up to three arbitrarily chosen and widely separated lines in the visible and near-infrared spectral range (380 nm-900 nm). The spectral resolution is 180,000. The High Altitude Observatory in Boulder, Colorado is leading the design and construction of the ViSP. The ViSP has passed its PDR and is now working towards a critical design review scheduled for 2012.

2.2.3. Visible Tunable Filter (VTF)

The central mission of the VTF is to spectrally isolate narrow-bandpass images of the Sun the highest possible spatial and temporal resolution images from the ATST telescope. Observations with this instrument will allow rapid imaging spectroscopy, Stokes imaging polarimetry, accurate surface photometry, and spectroheliograms that will result in Doppler velocity maps, transverse flows, and imaging magnetograms that track evolutionary changes of solar activity.

The effort led by the Kiepenheuer Institut für Sonnenphysik in Freiburg, Germany as a partnership contribution to the ATST. The VTF will produce diffraction-limited narrow-band 2D spectroscopy and polarimetry. Its multi-etalon Fabry-Pérot filter operates from 515 nm to 860 nm. The spectral resolution of the Fabry-Perot filter system will be 2.5 pm and thus an order of magnitude better than that of the VBI. The FOV is limited to a maximum of 1 arcmin. This type of instrument has been and continues to be highly successful at current solar telescopes (Cavallini 2006; Scharmer et al. 2008).

2.2.4. Diffraction Limited Near-IR Spectro-Polarimeter (DL-NIRSP)

The primary purpose of the DL-NIRSP is the study of the solar magnetic fields at high spatial and spectral resolution at near infrared wavelengths from 900 nm to 2500 nm. While the spatial resolution of the ATST decreases with increasing wavelength, the magnetic resolution of the Zeeman effect increases with increasing wavelength. The advantages to observing at longer wavelengths and specific science drivers that this instrument will address were discussed in the introduction. A DL-NIRSP like instrument
(FIRS) has just been commissioned at the Dunn Solar Telescope and has provided valuable guidance for the DL-NIRSP design (Jaeggli et al. 2010). The instrument will have a spectral resolving power of up to 200,000 and will provide diffraction-limited spectropolarimetry. Key features of the DL-NIRSP are a multi-slit capability for increased scan efficiency and rapid cadence, the capability to observe photospheric and chromospheric wavelengths simultaneously and a fiber feed that enables moderate resolution coronal polarimetry utilizing the Fe xiii (1075 nm) coronal emission line. The University of Hawaii’s Institute for Astronomy (IfA) is leading the DL-NIRSP development effort. The instrument has successfully passed its PDR and is now progressing towards CDR.

2.2.5. Cryogenic Near Infrared Spectro-Polarimeter

The primary purpose of the Cryogenic Near-IR Spectro-Polarimeter (Cryo-NIRSP) is the study of the solar magnetic fields over a large field-of-view at thermal infrared wavelengths in the solar corona. This instrument is designed and build by the Institute for Astronomy of the University of Hawaii. The Cryo-NIRSP will measure the full polarization state (Stokes $I$, $Q$, $U$ and $V$) of spectral lines in the near infrared wavelength regime from 1000 nm to 5000 nm. The instrument will be utilized for both on-disk observations and off-limb coronal spectroscopy and spectropolarimetry. The coronal spectral lines have very low intensity, measured in millionths of the brightness of the solar disk, and have much larger spectroscopic line widths than photospheric lines because the coronal plasma has a temperature in the millions of Kelvins. In some cases where prominences are studies, the spectral lines are much brighter and are cooler, representing chromospheric temperatures of only 8000 K. The Cryo-NIRSP is the primary
coronal instrument and operates in the moderate resolution (1 arcsec) and high photon flux regime. The Cryo-NIRSP does not utilize the adaptive optics system and currently is not envisioned to operate simultaneously with other instruments. Science goals include but are not limited to measuring coronal magnetic fields and their dynamic evolution, wave diagnostics of the coronal structure, CO dynamics, molecular spectroscopy in e.g. sunspots and Hanle scattering spectropolarimetry. The Cryo-NIRSP has a large field of view and, by trading spatial and spectral resolution for signal to noise, is capable of coronal magnetic field measurements in Fe\textsubscript{xii} (1075 nm) and Si\textsubscript{ix} (3935 nm) taking advantage of the low sky background at IR wavelengths and reduced scattering from optical surfaces. The spectral resolving power is 30,000. When operated at higher spatial resolution, it can provide solar surface observations across its bandpass including the important CO bands at 2333 nm and 4666 nm. The instrument has successfully passed its PDR and is now progressing towards CDR.

2.2.6. Facility Cameras

Two camera designs are planned for ATST instruments, one visible and one infrared. All infrared detector requirements are met by a Teledyne Hawaii2-RG camera and it is the current baseline, though other vendors will be surveyed before infrared camera acquisition. The plan for visible wavelength sensors presented at the FDR is to wait as late as possible in construction before acquisition, then procure the camera that best meets requirements. Currently that camera is the Fairchild/Andor/PCS sCMOS design with 2560×2180 pixels, smaller than the 4k×4k called for by some instruments but with good frame rate, quantum efficiency, and extremely low read noise. It is likely there will be camera advances between now and the time a purchase is required.

2.2.7. Data Handling System (DHS)

The Data Handling System is one of ATST’s four principal systems and standardizes the flow of data within ATST. Its core functionality covers several aspects when handling large data streams: the data transport infrastructure, processing pipeline architecture, quality assurance functionality, and data storage. Finally, its design includes a mechanism to efficiently transport the data from the telescope site. ATST subsystems where necessary, all first-light instruments, as well as future facility instruments will use the ATST Data Handling System for these tasks. Key Requirements include a data transport bandwidth of at least 960 MB/s, a processing pipeline with scalable hardware and plugin-software that allows sufficient online Quality Assurance. Storage capacity on the mountain will be sufficient to buffer at least 3 days of observational data even though data will be transported to the base facility on a daily basis.

Wherever possible, the ATST DHS utilizes standardized, off-the-shelf technology to ensure easy maintenance and the ability to upgrade to future technology. Examples include the use of standard 10 Gbit networking hardware for fast data transport, or general purpose graphical processing units (GPGPUs) to meet the computational requirements for the processing pipeline and quality assurance system. Their power can be easily harnessed by systems using the DHS through a simple, plugin based software interface to the DHS. The ATST DHS is currently under construction and a majority of its functionality (albeit scaled down in performance) will be made available to its prospective users in the near future to enable these systems to ease their development early on in the process.
3. ATST Operations Planning

ATST operations, including data handling and dissemination will be much more efficient compared to the operations of current NSO or similar facilities. ATST operational concepts have been developed and will be refined during the construction phase. These concepts build on the lessons learnt from recent spacecraft operations such as TRACE, HINODE and SDO. Efficient operational modes such as Service Observations will make more efficient use of the available observing time. The NSO Data Center at NSO headquarters will provide science ready ATST data products to the solar physics community. An open data policy allows for maximum science productivity.

In order to achieve highest possible operational efficiency and guarantee maximized high-impact scientific output NSO will abandon the traditional model of scheduling observing time, in which only one PI has exclusive access to the telescope during a fixed block of observing time and with some help from the observing staff performs the observations. Instead, Service Observations that allow for flexible scheduling will be implemented. Scientific observing requests will be efficiently pooled, queued and executed only when solar conditions (target availability) and seeing conditions are suitable. Only the observatory expert ATST operations staff will operate the telescope, instruments and all associated support systems. Service time is dynamic and the observatory staff is responsible on a daily basis for real-time decisions regarding what programs out of a list ranked on scientific merit are executed and what instruments will be operated. The service mode does not require the physical presence of the proposal PI. Remote participation in observations by the PI is enabled via telecommunication equipment.

The service mode allows making efficient use of target availability, weather conditions and technical readiness and supports a broad range of different programs. This mode is amenable to target of opportunity observations and can be used to perform (long-term) synoptic programs, and does allow for coordinated programs or other programs where special time constraints are given (e.g., rocket launch, balloon or space experiment). The service mode also supports maintenance and engineering tasks or special calibration measurements. Those often can be performed during weather conditions that are not suitable for science observations. Service Mode provides flexible scheduling tools that avoid usage of prime observing time for these calibration measurements. To fully support service mode observing, the on-site observatory staff will have a number of key scientific and engineering "actors" that conduct and support the observations. These include the Resident Astronomer, Operators, Engineers, Instrument Scientists, and a Wavefront Correction Specialist. The RA is the final authority for daily scheduling and execution of observations. The RA role is in some ways comparable to the Hinode Chief Observer. Instrument Scientist and Wavefront Correction Specialist are expert users of complex instrument and adaptive optics system who ensure that these systems are properly calibrated and operate with consistent performance and according to specification as well as providing support to users in preparing and conducting observations.

The Service Mode is expected to be the predominant observing mode. In addition, the ATST will make available an Access Mode when real-time decisions, and close interactions with, the PI are necessary. The Access Mode is particularly tailored to support instrument development efforts, programs that have special-time constraints, and special technical tasks. Hence, access time is offered and encouraged only during limited periods of time and has to be balanced with service mode operations in order
to optimize scientific output. During access time the PI or his/her designee and Co-
Pis may be either granted physical access to the facility or can participate remotely
from the Maui base facility. In contrast to the PI-Mode based operations of "highly
flexible" instrument setups at NSO’s current facilities, ATST’s emphasis on Service
Mode operation of facility class instruments in conjunction with an open data policy
will enable ATST to provide consistent data products that can be processed, archived
and disseminated by the NSO data center.

Acknowledgments. The National Science Foundation (NSF) through the National
Solar Observatory (NSO) funds the ATST Project. The NSO is operated under a co-
operative agreement between the Association of Universities for Research in Astronomy,
Inc. (AURA) and NSF. The ATST represents a collaboration of 20 plus institutions, re-
reflecting a broad segment of the solar physics community. The NSO is the Principal In-
vestigator (PI) institution, and the co-PI institutions are the High Altitude Observatory,
New Jersey Institute of Technology’s Center for Solar Research, University of Hawai’i’s
Institute for Astronomy, and the University of Chicago Department of Astronomy and
Astrophysics.

References

Society of the Pacific Conference Series, 309
Series, 319
Kuhn, J., Lin, H., Jaeggli, S., Arnaud, J., & Mickey, D. 2006, in 36th COSPAR Scientific
Assembly, vol. 36, #1643
Lites, B. W., Kubo, M., Sucas-Navarro, H., Berger, T., Frank, Z., Shine, R., Tarbell, T., Title,
Nelson, P. G., Casini, R., de Wijn, A. G., & Knoelker, M. 2010, in Ground-based and Airborne
Instrumentation for Astronomy III, edited by I. S. McLean, S. K. Ramsay, & H. Takami,
vol. 7735 of SPIE Conference Series, 77358C
Rimmele, T. R., & the ATST Team 2008, Advances in Space Research, 42, 78
P., Phelps, L., Marshall, H., Goodrich, B., Richards, K., Hegwer, S., Kneale, R., &
Ditsler, J. 2010, in Ground-based and Airborne Telescopes III, edited by L. M. Stepp,
Scharmer, G. B., Narayan, G., Hillberg, T., de la Cruz Rodríguez, J., Löfdahl, M. G., Kiselman,
— 2011b, Central European Astrophysical Bulletin, 35, 1
Wöger, F., Uitenbroek, H., Tritschler, A., McBride, W., Elmore, D., Rimmele, T., Cowan, B.,
Wampler, S., & Goodrich, B. 2010, in Ground-based and Airborne Instrumentation for
Conference Series, 773521
Wöger, F., & von der Lühe, O. 2007, Appl.Optics, 46, 8015