The ATST Project is funded by the National Science Foundation through the National Solar Observatory which is operated by the Association of Universities for Research in Astronomy (AURA), Inc.

ATST Will:

- Clearly resolve fundamental astrophysical processes at the spatial scale needed to test models
- Provide a high photon flux for accurate and precise measurements of physical parameters throughout the solar atmosphere
  - High signal to noise spectro-polarimetry of magnetic field on its elemental scale
  - Measure magnetic strength and direction, temperature and velocity, on the short time scales of the dynamic solar atmosphere
- Directly measure coronal and chromospheric magnetic fields
- Observationally test models of:
  - Magneto-convection
  - Flux emergence and annihilation
  - Flux transport
  - Flux tube formation and evolution
  - Sunspot magnetic fields and flows
  - Atmospheric heating
  - Solar Activity
- Enable, complement and enhance planned space missions
ATST Collaboration

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  - National Solar Observatory
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    • Jim Oschmann, Project Manager

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Southwest Research Institute
Princeton University, Plasma Physics Laboratory
Why an ATST

Theory and Modeling have gone beyond our ability to test observationally

- Numerical simulation of magneto-convection (courtesy of Fausto Cattaneo)
- As viewed with a diffraction limited 4-m telescope
- As viewed with a diffraction limited 1-m telescope


"It easy to have a theory about something that is not resolved in the telescope."

Major Question ATST will Address

- How are the highly intermittent magnetic fields observed at the solar surface generated by dynamo processes and how are they dissipated?
- What magnetic configurations and evolutionary paths lead to flares and coronal mass ejections
- What mechanisms are responsible for variations in the spectral and total irradiance of the Sun?
• ATST Is a NSF Initiative That Will Complement LWS Missions
  – Extend Wavelength Coverage to Thermal IR
  – Extend Spatial Resolution Below 0.1"
  – Provide Rapid Cadence Polarimetry of Active Regions
  – Provide Instrument Flexibility & Larger Set of Science Objectives

• ATST Will Be Operated Simultaneously With Missions Like SDO
  – SDO Has Large FOV and Provides Connections Between Surface Activity and the Outer Solar Atmosphere and the Interplanetary Space
  – ATST Has Small Field of View but Provides the Critical Small-scale Physics of Magnetic Filed-plasma Interactions
  – ATST Can Provide Follow-on Observations With Rapid Changes in Focal Plane Instrumentation
Dynamics of Flux Tubes

We need to measure and understand

- Interaction of flux tubes with convection - Generation of MHD waves
- Channels for energy transport - chromospheric/ coronal heating
- Basic elements, “Building blocks” of solar magnetism
- Luminosity variations – how do flux tubes modify energy transport as a function of wavelength?
- Modification of p-mode frequencies
- Foot-point motion - Activity (e.g. flares)

Must be able to measure rapidly changing Stokes vectors

Shock wave propagating along a flux tube:

Courtesy of: Oskar. Steiner
Convection
The “Action” is in the Narrow Downdrafts

- Not a hierarchy of eddies!
- Convection characterized by turbulent narrow downdrafts and smooth, fairly laminar upflows.
- Convection is driven by radiative cooling in a thin surface thermal boundary layer produces low entropy gas that forms the cores of downdrafts.
- Vorticity primarily in intergranular lanes and downdrafts

- Magnetic field is carried to bottom of convection zone by downdrafts.
- Turnover time at bottom of convection zone is months.
- Only small fraction of plasma starting up from bottom of convection zone reaches the surface.

- How do small scale and large scale dynamos interact?

How are p-mode oscillations excited?

Acoustic events in the lanes feed the energy into p-modes
- The action is in the intergranular lanes (< 0.1)
- Turbulent downdrafts cause “acoustic noise”.
- Laminar upflows are “quiet”.

Oscillations are excited near the surface.
PdV work of nonadiabatic pressure fluctuations is primary mode excitation mechanism

To verify:
Need to resolve substructure in intergranular lanes.
The canonical 0.1 is not good enough!
How do small scale and large scale dynamos interact?

Answers Need: Measurements of Weak Fields in e.g. the NIR – Need higher resolution and more photons!

Current Observations:
• Mixed Polarity Fields
  Observed in “Quiet” Sun
• Sensitivity V/I ~ 10E-4
  • 100-500G

BUT:
• Insufficient spatial resolution (>1") because of seeing and telescope aperture
• Insufficient temporal resolution (5 min)
• Insufficient sensitivity: no vector field measurements!

Courtesy of: Lin&Rimmele1999

A number of competing models of CMEs exist

We need data!
• Magnetic field measurements in the chromosphere and corona?
  – Prominence magnetic field measurements
  – Magnetic fields in the coronal helmets.
• Pre- and post CME field configuration
• Pre- and post flare loop systems
• Dynamics of coronal field
• Heating Mechanisms
• Coronal Loops (separators or current sheets?)
• Wave Phenomena
• Kill a few models!!

Courtesy B.C. Low
**Progress in Solar Physics Needs:**

- **More Quantitative Data:**
  - Full Stokes Vector Polarimetry
  - Full line spectroscopy with good spectral resolution
- **A “Systems Approach” to get a (more) complete picture**
  - Multi-line, multi-wavelength observations
  - NIR, Thermal IR
- **Better Spatial Resolution!**
- **Higher Temporal Resolution!**
- **Photons, Photons !!!**

  *We need the ATST*

**Key drivers of telescope design:**

- **Image Quality**
  - Diffraction limited optical spectroscopy & polarimetry
  - Near IR spectral polarimetry
  - Near IR coronal magnetometry
- **Polarization**
  - Optical and IR polarimetry use
- **Scattered Light**
  - Near IR coronal magnetometry

**Requirements**

- **Aperture:** 4 m
- **Resolution:** diffraction limited:
  - within isoplanatic patch (conventional AO)
  - over ~2 arcmin using MCAO (upgrade)
- **Adaptive Optics:** Strehl ratio: >0.3, goal of S > 0.6 during good seeing
- **FOV:** 3 arcmin (goal 5 arcmin)
- **Wavelength Coverage:** 300 nm - 28 micron
- **Polarization Accuracy:** $10^{-4}$ (low instrumental polarization)
- **Polarization Sensitivity:** limited by photon statistics down to $10^{-5}$
- **Low Scattered Light:**
  - e.g. sunspots: 1% of surrounding photosphere
  - Corona: $< 10^{-6}$ at $R = 1.1R_e$; $\lambda = 1\mu$
- **Coronagraph:** in the NIR and IR
- **Flexibility:** e.g., Combine various post-focus instruments
- **Adaptability:** e.g., try out new ideas, bring your own instrument
18 scientific use cases lead to specific high-level requirements:

• **Resolution: 0.03 arcsec (25 km) at 500 nm**
  ⇒ 4-meter aperture working at the diffraction limit
  ⇒ High-order adaptive optics, MCAO upgrade option
  ⇒ Minimal self-induced seeing

• **Photon flux: Integration times as short as 1 msec at spectral resolution as high as 1-2 picometers**
  ⇒ 12 m² collecting area (4-meter aperture)

• **Wavelength coverage: 300 nm to 28 µm**
  ⇒ All-reflecting optics, no windows, no evacuated column

• **Scattered light and coronagraphy: 2.5_10⁻⁵ of on-disk irradiance 1.1 solar radii (1.6 arcmin) above the limb**
  ⇒ Off-axis optical design
  ⇒ Prime-focus occulting
  ⇒ In-situ mirror cleaning and washing
  ⇒ Filtered air

• **Field of view: 3 arcmin unvignetted**
  ⇒ Gregorian optical configuration allowing heat-rejection opportunity at prime focus

• **Polarimetry: Sensitivity of 10⁻⁵ I₀**
  ⇒ Facility-level signal modulation and analysis
  ⇒ Specialized facility-level charge-caching detector packages

• **Operational modes: Highly flexible, multi-instrument configurations are required**
  ⇒ Large coudé observing area
  ⇒ High level of instrumental commonality
  ⇒ Innovative instrument-control software

• **Lifetime: 30 to 40-year life expectancy**
  ⇒ Flexible design with upgrade paths
Optical Design Overview

The Off-axis Telescope

ATST Baseline Design

- Aperture: 4m
- Gregorian
- Off-Axis
  - Unobstructed Aperture
  - Clean PSF, High Strehl
  - Easy access to: prime focus, heat stop, occulting, secondary
  - No hot objects in beam > Internal seeing control easier
  - Scattered light control
  - Rotating spiders cause problems with WFS flat field
- Alt-Az
- Conventional Adaptive Optics (MCAO upgrade)
- Tip/tilt secondary
- Internal Seeing Control (thermal control of optics&structure)
- Contamination Control
- Enclosure - Hybrid

Off-axis advantages

- There is no obstruction of the beam by the secondary mirror
- There is no diffraction from the secondary support structure to degrade coronal images.
- Coolant and other services can be delivered to the secondary mirror without crossing the beam.
Diffraction-Limited Imaging

Delivering diffraction limited images requires...

- Integrated high-order (~1000 DoF) adaptive optics
- MCAO upgrade path
- The best possible site
- Controlling the temperature of all insolated surfaces
- Robust active M1 mirror-support system that can deliver accurate surface figures at high zenith distances.

Site Selection and Preparation

- Six sites tested during past year +
  - Down selection to 3 Sites for phase II testing
  - Selection single site by November 2004
  - Begin EIS for high priority site January 2005
    - 12 months in schedule currently
- Final sites to test
  - Big Bear Solar Observatory, California
  - Mees Solar Observatory, Haleakala, Hawaii
  % NSO/Sacramento Peak Observatory, New Mexico
  % Observatorio Astronómico Nacional, San Pedro Mártir, Baja California, Mexico
  % Observatorio Roque de Los Muchachos, La Palma, Canary Islands, Spain
  % Panguitch Lake, Utah
Control of self-induced seeing is essential to meeting resolution requirements

- **Mirror Seeing**
- **Enclosure Seeing**
  - Exterior
  - Interior
- Insulated surfaces must be cooled close to or slightly below ambient air temperature

**Thermal Control – Heat Stop**

- 1 kilowatt/m$^2$ at M1 is concentrated to 2,500 kilowatts/m$^2$ at prime focus
  - 12,400 watts collected by M1 (the primary mirror)
  - 10,900 watts reflected by the heat stop
  - 1,200 watts absorbed and pumped away by the stop
  - 300 watts passed to M2 (~1 kilowatt/m$^2$)
  - 30 watts (10%) absorbed by M2
Thermal Control – Mirrors

M1 Cooling strategies
- Remove 1.4 kilowatts of power
- Wind flushing the top surface (natural or forced ventilation when required)
- Active cooling of the back with air jets using conditioned air 1-3 °C below ambient
- Six zones, each with its own fan and air/liquid heat exchanger

M2 Cooling strategies
- Remove 30 watts of power at similar power density to M1
- Wind flushing over the top surface
- Silicon carbide substrate for high conductivity
- Active cooling of the back with air jets, similar to M1.

Thermal Control – Enclosure

Hybrid, actively cooled co-rotating enclosure

- Wind throttling under high-wind conditions
- Active ventilation under low-wind conditions
- Dust infiltration control (during coronal observations)
- Shading of structures
- Weather protection
Coronal Observations

- Stray light must not contribute more than $2.5 \times 10^{-5}$ of on-disk irradiance 1.1 solar radii (1.6 arcmin) from the limb
  - Dust first, mirror polish second
  - Shut the vents (relaxed resolution requirement)
  - Filter the air
  - Clean and wash primary in situ

Facility Instrument Systems

- Integrated polarization fore-optics for calibration and modulation.
- Facility camera systems for instrumentation at Gregorian and coude stations.
- Standardized fixtures, scanning, and imaging systems
- Interconnects to data handling, cryogens, vacuum, and other utilities.
- Flexible, highly configurable instrument-control software that supports multiple-instrument observations as a single “virtual instrument.”

First Generations Facility Instruments
- Visible Light Broadband Imager
- Visible Spectro-polarimeter
- Near IR Spectro-polarimeter
  - Gregorian module for coronal observations
  - Coude module for on-disk observations
- Visible Tunable Filter
Construction Cost Estimates
(In Year 2003 $US Dollars)

- f/3 System Cost: $134M
- Cost Includes:
  - 20% Total Contingency
  - (3x) $6M Instrument
- Inflated to Year 2013, System Cost: $161M

ATST Timeline
With and Without Long Lead Items

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Scientific and Technical Advisory Groups

- Final Select Site
- Demonstrate High-Order AO system
- Schedule with Early Mirror Procurement
- Schedule with mirror Procurement at beginning of construction phase
- Mirror Procurement
- Mirror Procurement
- Construction
- Integration
- Integration
- Operation