Project Documentation
Specification #0001
Revision B

ATST Science Requirements Document

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Revision Summary:

1. Date: 21 March 2002
   Revision: 04b
   Changes: Reformatted for internal consistency, added TOC.

2. Date: 13 August 2002
   Revision: 04c
   Changes: Reformatted to new ATST document format.

3. Date: 19 September 2002
   Revision: 05
   Changes: Major revision. Incorporated ASWG comments; new science cases; changed scattered light specs based on coronal working group report, revised image quality specs according to ASWG discussions; instrument SRDs separate documents.

4. Date: 07 October 2002
   Revision: 05a
   Changes: Modified list of first generation instrumentation. Clarification of image quality requirements.

5. Date: 15 October 2002
   Revision: 05b
   Changes: Include paragraph about spicules (section 3.2.3)

6. Date: 17 November 2002
   Revision: 06
   Changes: Includes ASWG comments from Tucson meeting, Oct 2002

7. Date: 11 August 2003
   Revision: A
   Changes: Included revised paragraph on “Coronal Plasmoid search by Matt Penn”. Some minor formatting changes. Added some references.

8. Date: 12 December 2005
   Revision: B
   Changes: Included comments specific to coronal magnetometry to Section 2.2. Modified FOV (per Change Request ECR-0003) and AO top-level science requirements (per ECR-0002) in Table 1 after December 2005 SWG meeting. Modified resolution requirement in Section 4.1 per ECR-0002 (as above). Modified Section 4.5, FOV (as above). Modified Section 5.1 item four to add that AO should be used. Modified Section 5.1 to reflect changes in AO requirements (as above).

WAIVERS: The following waivers are applicable to this specification:

1. RFW-0038: Delivered Image Quality at 4.8 microns (05-Nov-2013)

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1. INTRODUCTION

The ATST will be the largest, and most capable solar telescope in the world. The ATST will replace the 0.8-m and 1.5-m general-purpose solar telescopes, built in the 1960's and 1970's and currently operated by the National Solar Observatory, and will complement and provide support- and context observations for planned space missions such as SOLAR-B, Solar Probe, Solar Orbiter, Solar Dynamics Observatory (SDO), and the Solar Terrestrial Relational Observatory (STEREO). ATST will serve the US and international solar physics community for at least two decades. It is therefore a requirement that ATST be designed as a facility (as opposed to an experiment or space mission of well defined scope) that has the capability and flexibility to address a large number of scientific questions and, in the long term, allows adaptability to new scientific challenges. It is somewhat of a challenge to formulate a set of scientific requirements that covers this long-term perspective of ATST. The approach taken here is the following.

The most demanding observational requirements, as currently envisioned, lead to the most stringent technical requirements for telescope and instruments. This document therefore focuses on these demanding observational requirements, which in turn drive the design requirements and design goals. In this document we will specify minimum Science Requirements that have to be met by the ATST facility. In addition, in some cases a more demanding goal will be specified which the engineering team should strive to meet if possible given budgetary and feasibility constraints.

After a summary of the top level science requirements (section 2), which are discussed in more detail in the ATST proposal (http://atst.nso.edu/proposal/), a number of specific science goals and the corresponding observational requirements are discussed (section 3). A compilation of these observational requirements is used to formulate top-level telescope requirements (section 4), which are detailed further in section 5.

2. TOP LEVEL SCIENCE REQUIREMENTS

2.1. SPATIAL RESOLUTION

A main driver for a large-aperture solar telescope is the need to spatially resolve the fundamental astrophysical processes at their intrinsic scales in the solar atmosphere. It has long been argued that the fundamental spatial scales are the photon mean-free path and the pressure scale height. To resolve both fundamental length scales in the deepest accessible layers of the solar atmosphere, a resolution of 70 km or 0.1 arcsec is required. However, modern numerical simulations with a resolution of 10 km as well as inference from the best available images have suggested that crucial physical processes occur on even smaller scales of a few tens of kilometers. Resolving spatial scales on the order of a few tens of kilometers is of utmost importance to be able to test various physical models and thus understand how the physics of the small scales ties into the larger problems. An example is the question of what causes the variations of the solar radiative output, which impacts the terrestrial climate. The Sun's luminosity increases with solar activity. Since the smallest magnetic elements contribute most to the flux excess, it is of particular importance to study and understand the physical properties of these dynamic structures. Unfortunately, current solar telescopes cannot even resolve such scales at visible wavelength because of their limited aperture.

This impasse is recognized by the astronomy community, which has advanced strong scientific arguments for a large-aperture solar telescope. The most recent arguments are also presented in the latest Decadal Survey of Astronomy and the NAS/NRC study of ground-based solar astronomy. These reports make a strong and persuasive case for high-resolution studies of the solar atmosphere and the Sun's magnetic field.

As its highest priority science driver ATST shall provide high resolution and high sensitivity observations of the highly dynamic solar magnetic fields throughout the solar atmosphere and is therefore a crucial tool needed for trying to understand this complex physical system. Models and simulations predict magnetic structures with spatial scales of about 30km (Cattaneo 1999, Stein 2002). In order to resolve these structures at a wavelength of 630.2 nm, the wavelength of the important FeI lines used for most polarimetric studies, **the ATST shall have a minimum aperture of 4m (1.22 λ/D= 30km). Using adaptive optics the ATST shall provide diffraction limited observations of high Strehl within the isoplanatic patch for visible and infrared wavelengths.**

2.2. POLARIMETRY

The ability to perform precision polarimetry at high spatial resolution is a top priority requirement for the ATST. The solar atmosphere is structured by magnetic fields on very small scales and dynamic events such as flares and coronal mass ejections are driven by the interaction of convective flows and magnetic fields. To test theoretical models of solar magnetism , it is essential to perform high-resolution and high precision vector polarimetry throughout the solar atmosphere. The precise measurements of the magnetic Stokes vector needed to accurately map out the full vector magnetic field is a fundamental goal for the ATST. **The ATST shall perform accurate and precise polarimetry of solar fine structure**. The **Polarization sensitivity**, defined as the amount of fractional polarization that can be detected above a (spatially and/or spectrally) constant background, **shall be $1 \bullet 10^{-5}$** (limited by photon noise). The **Polarization accuracy**, defined as the absolute error in the measured fractional polarization, **shall be $5 \bullet 10^{-4}$**. For special applications such a coronal magnetometry higher polarimetric accuracy may be required. This increased requirement is very specific to one instrument and will be specified in the ISRD for the coronal magnetometer.

2.3. PHOTON FLUX

The requirement for a large photon collecting area is an equally strong driver toward large aperture as is angular resolution. Observations of the faint corona are inherently photon starved. The fact that in many cases observations of structures and phenomena on the solar disk are also suffering from a lack of photons may be less obvious. The reason is that the solar atmosphere 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. **The ATST shall provide sufficient collecting area (12 m^2 minimum) to enable accurate and precise measurements of physical parameters, such as magnetic strength and direction, temperature and velocity, on the short time scales involved and in all layers of the solar atmosphere (Photosphere, Chromosphere and Corona).**

2.4. WAVELENGTH COVERAGE

The ATST shall permit exploitation of the infrared. The near-infrared spectrum around 1.6 μm has many advantages (Solanki, Ruedi &Livingston 1992), particularly for precise measurements of the recently discovered weak, small- scale magnetic fields that cover the entire solar surface and could be the signature of local dynamo action. **A minimum aperture of 4 m** is needed to resolve these features at 0.1 arcsec in the near infrared. Furthermore, the infrared beyond 1.5 μm provides particularly powerful diagnostics of magnetic field, temperature, and velocity at the upper layers of the solar atmosphere. For example, observations using the CO lines at 4.7 μm have already changed significantly our picture of stellar chromospheres and have resulted in a better physical understanding of this important layer in the solar atmosphere (Ayres 2002). The 12.3 μm emission lines of MgI are the most magnetically sensitive lines in the solar spectrum. Using the Mg I lines fields down to 100 Gauss can be measured directly from their Zeeman splitting. With explicit radiative transfer modeling, even lower field strengths can be observed, making these lines excellently suited to map the weak inter-network magnetic fields. Observations combining 12- μm polarimetry with magnetic field data from other wavelengths will yield the three-dimensional field structure in the photosphere and the lower chromosphere, i.e., in the important regime where the field becomes de-coupled from gas motion. To exploit the unique diagnostic tools that are now becoming accessible in the IR solar spectrum with the newly developed IR detector technology requires the largest possible telescope aperture. The ATST shall provide improvement by a factor of nearly three in linear spatial resolution over the largest currently available solar IR facility, which translates into a factor of nearly ten in the ability to discriminate small 2-D cool or hot spots on a diffuse background. **The ATST wavelength coverage shall be 300nm – 28 micron.**

2.5. SCATTERED LIGHT AND CORONAGRAPHY

Space missions like Yohkoh, SoHO, and TRACE have advanced our knowledge of the Sun's corona enormously and have renewed interest in diverse coronal plasma problems ranging from how coronal mass ejections are formed and accelerated, to how photospheric magnetic fields drive the inverted coronal temperature structure. These successful space missions have further demonstrated the need for accurate measurements of the coronal magnetic field (Lin, Penn & Tomczyk 2000; Low 2001). The magnetic sensitivity of the IR lines and the low atmospheric scattering conditions in the IR are important motivation to utilize the ATST for exploring the IR coronal spectrum. The coronal emission lines Fe XIII 1.0747 micron and the recently confirmed Si IX line at 3.9 micron provide excellent diagnostic tools for studying coronal magnetic fields (Judge et al. 2001, Kuhn et al. 1999, Judge et al. 2002).

ATST shall provide low scattered light observations and coronagraphic capabilities in the infrared to allow spectroscopy of coronal structures and measurements of coronal magnetic fields.

2.6. FIELD OF VIEW

The ATST shall provide a minimum usable Field-of-View (FOV) of 3 arcmin minimum (goal 5 arcmin) to allow observations of large active regions.

2.7. OPERATIONAL MODES

The solar atmosphere provides an ideal laboratory to study the dynamic interaction of magnetic fields and plasma. Magnetoconvection is a fundamental process that is at the heart of many key problems of solar astronomy and astrophysics in general. For example, understanding the evolution of magnetic flux in the lower atmosphere is essential in addressing the most pressing problems in solar physics, such as the origin of magnetic fields, the irradiance variability, and heating of the corona. Magnetic fields provide channels for energy and momentum transport, thereby closely coupling the dynamics of the upper atmosphere to the convectively driven dynamic behavior of the magnetic field near the surface of the Sun. The photosphere represents a crucial interaction region where energy is easily transformed from one form to another. For example, kinetic energy from convective motion can be easily transformed into magnetic energy. The energy stored in the magnetic field is eventually dissipated at higher layers of the solar atmosphere, sometimes in the form of violent flares and coronal mass ejections (CMEs) that ultimately drive space weather and affect the Earth. The different layers of the solar atmosphere, namely the photosphere, the chromosphere and the corona are connected through the magnetic field and therefore have to be treated as one system, rather than individual layers. **In order to obtain a maximum on information describing this system the ATST shall provide access to a broad set of diagnostics, from visible to thermal infrared wavelengths. The ATST shall provide the flexibility to combine various post focus instruments, which, for example cover different wavelengths regimes, and operate them simultaneously. The ATST shall be able to perform joint observations with space missions and other ground based facilities.**

2.8. LIFETIME

ATST is expected to serve the international solar community for 30-40 years. This means that in addition to being able to address the many scientific challenges of today **ATST shall be able to adapt to new scientific challenges as they develop. The flexibility and adaptability that has been achieved with current solar telescopes such as the Dunn Solar Telescope are therefore important requirements**. For example, the ATST design shall allow implementation of new technologies such as Multi-conjugate adaptive optics (MCAO) once these technologies are developed.

Aperture:	4m
FOV:	5 arcmin at prime focus and at Nasmyth, 2 arcmin square (2.83 circular) at coudé, goal of 5 arcmin at coudé
Resolution:	*Conventional AO Case*: diffraction limited within isoplanatic patch for visible and IR wavelengths. *MCAO (upgrade option):* diffraction limited over > 1 arcmin FOV
Adaptive Optics:	Strehl (500nm): >0.3 for r0 > 7cm seeing, Strehl(630nm) >0.6 for r0(630)nm > 20cm
Wavelength Coverage:	300 nm - 28 μm at Nasmyth, 380 – 28 μm at Coudé
Polarization Accuracy:	Better than 5×10^{-4} of intensity
Polarization Sensitivity	limited by photon statistics down to 10^{-5} I_c
Coronagraphic:	In the NIR and IR
Instruments	Well instrumented - access to a broad set of diagnostics, from visible to thermal infrared wavelengths
Operational Modes	flexibility to combine various post focus instruments and operate them simultaneously flexibility to integrate user supplied instruments ability to perform joint observations with space missions
Lifetime	30 –40 Years

Table 1: Summary Top Level Science Requirements

The following sections summarize some of the most pressing science questions that will be addressed with the ATST. A detailed description of the ATST science goals can be found in the ATST proposal (atst.nso.edu/proposal) and in section 3.

2.9. FLUX TUBES, THE BUILDING BLOCKS OF STELLAR MAGNETIC FIELDS

Observations have established that the photospheric magnetic field is organized in small fibrils or flux tubes. These structures are mostly unresolved by current telescopes. Flux tubes are the most likely channels for transporting energy into the upper atmosphere, which is the source of UV and X-ray radiation from the Sun, which in turn affects the Earth’s atmosphere. Detailed observations of these fundamental building blocks of stellar magnetic fields are crucial for our understanding not only of the activity and heating of the outer atmospheres of late-type stars, but also of other astrophysical situations such as the accretion disks of compact objects, or proto-planetary environments. The diffraction limited resolution of ATST will be 0.”03 at 500nm and 0.”08 at 1.6 microns. At this resolution ATST will provide the required spectroscopy and polarimetry at an angular resolution to explore the enigmatic flux tube structures.

2.10. MAGNETIC FIELD GENERATION AND LOCAL DYNAMOS

To understand solar activity and solar variability, we need to understand how magnetic fields are generated and how they are destroyed. The 11-year sunspot cycle and the corresponding 22-year magnetic cycle are still shrouded in mystery. Global dynamo models that attempt to explain large-scale solar magnetic fields are based on mean field theories. Dynamo action of a more turbulent nature in the convection zone may be an essential ingredient to a complete solar dynamo model. Local dynamos may produce the small-scale magnetic flux tubes recently observed to cover the entire Sun. This “magnetic carpet” continually renews itself on a time scale of a few days at most and its flux may be comparable to that in active regions. The ATST will make it possible to directly observe such local dynamo action at the surface of the Sun. The ATST will measure the turbulent vorticity and the diffusion of small-scale magnetic fields and determine how they evolve with the solar cycle.

The ATST will address the following fundamental questions: How do strong fields and weak fields interact? How are both generated? How do they disappear? Does the weak-field component have global importance and what is its significance for the solar cycle?

The ATST will address these fundamental questions by resolving individual magnetic flux tubes and observing their emergence and dynamics. It will measure distribution functions of field strength, field direction and flux tube sizes and compare these with theoretical models. The ATST will observe plasma motions and relate them to the flux tube dynamics.

2.11. INTERACTION OF MAGNETIC FIELDS AND MASS FLOWS

In sunspots, the total magnetic field is large enough to completely dominate the hydrodynamic behavior of the local gas, a regime very different from that of the rest of the solar photosphere. Numerical simulations and theoretical models predict dynamical phenomena, such as oscillatory convection in the strong-field regions of sunspot umbrae, flows at the speed of sound along penumbral filaments and oscillations and wave phenomena. To verify the predictions of numerical simulations of sunspots and ultimately answer such fundamental questions as “Why do sunspots exist?” require an extremely capable instrument. High-resolution (<0.1 arcsec) vector polarimetry combined with high sensitivity (requires high photon flux) and low-scattering optics are required. Understanding the interaction of magnetic flux and mass flows is crucial for our understanding of the behavior of magnetic fields from the scales of planetary magnetospheres, to star-forming regions, to supernova remnants, to clusters of galaxies. Sunspots allow us to test those theories in a regime where magnetic fields dominate mass flows.

2.12. FLARES AND MASS EJECTIONS

It is commonly believed that solar flares represent a process of rapid transformation of the magnetic energy of active regions into the kinetic energy of energetic particles and plasma flows and heat. Detection of variations of magnetic field associated with solar flares has been one of the most important problems of solar physics for many years. Such detection would provide direct evidence of magnetic energy release in the flares. An important goal for the ATST will be to study the small-scale processes in solar flares. The ATST will also provide a new set of tools, in particular in the infrared, to measure magnetic fields at higher layers of the atmosphere. There is limited observational evidence that the distribution of electric currents and current helicity inside an active region varies with flares. Highly uniform sequences of high-resolution vector magnetograms of an active region before and after a flare are required to address this important issue.

Coronal mass ejections (CMEs) originate in large-scale magnetic arcades known as helmet streamers. These structures are known to contain twisted magnetic fields. According to the prevailing view, the arcade becomes dynamically unstable when its fields are twisted beyond some critical point. Field line footpoint motions in the photosphere have long been considered efficient ways to supply (or drain) magnetic shear and energy into (from) the coronal field. MHD simulations have identified critical magnetic shear conditions above which the arcade field will form current sheets, and magnetic reconnection processes will occur to cause active phenomena such as flares, CMEs, and prominence formation and eruption. It is thus important to measure field line footpoint motions and, if possible, the magnetic shear in active regions as well. Although measurements of the footpoint motion (in particular the horizontal plasma flow velocity) have improved considerably, the ATST will offer unprecedented high spatial and temporal resolution in measuring the field line footpoint motion.

More recently this view has been challenged by models in which the arcade emerges as a twisted flux rope or models in which small-scale photospheric reconnection events inject helicity into the corona. These hypothesized reconnection events occur when small (0.”1) photospheric flux elements cancel along the active region's magnetic neutral line. This model seems to contradict those models in which CMEs result from excessive twist in the arcade. Detailed observations of the flux emergence can reveal whether the emerging flux is introducing magnetic twist into the arcade, or changing the arcade's topology through footpoint cancellation. Only with higher spatial resolution vector measurements and good temporal resolution as will be provided by the ATST, however, can it be established, for example, that the rate and orientation of these cancellations is consistent with an observed change in the twist of the overlying arcade. Such observations are critical to distinguishing between competing models.

2.13. INHOMOGENEOUS STELLAR UPPER ATMOSPHERES

Measurements of CO absorption spectra near 4.7 μm show surprisingly cool clouds that appear to occupy much of the low chromosphere. Only a small fraction of the volume apparently is filled with hot gas, contrary to classical static models that exhibit a sharp temperature rise in those layers. The observed spectra can be explained by a new class of dynamic models of the solar atmosphere. However, the numerical simulations indicate that the temperature structures occur on spatial scales that cannot be resolved with current solar infrared telescopes. A test of the recent models requires a large-aperture solar telescope that provides access to the thermal infrared. Such observations would further explore the dynamical basis of the thermal bifurcation process, a fundamental source of atmospheric inhomogeneities in late-type stars. Spicules, the forest of hot jets that penetrate from the photosphere into the chromosphere, are clearly a MHD phenomenon that is not understood nor adequately modeled. Their role in the mass balance of the atmosphere is uncertain. Combined with UV observations (like those of TRACE), the ATST will allow us to resolve their nature.

2.14. MAGNETIC FIELDS AND STELLAR CORONAE

The origin and heating of the solar corona, and the coronae of late-type stars, are still mysteries. Most of the proposed scenarios are based on dynamic magnetic fields rooted at the 0.1-arcsec scale in the photosphere. However, none of the processes has been clearly identified by observations or theory. EUV and X-ray observations have gained in importance, but ground-based observations are still critical, not only to determine the forcing of the coronal fields by photospheric motions, but also for the measurement of the coronal magnetic field strength itself. This is important for developing and testing models of flares and coronal mass ejections, which propel magnetic field and plasma into inter-planetary space and induce geomagnetic disturbances. In particular, precise measurements of the coronal magnetic field strength and topology are needed in order to distinguish between different theoretical models. The ATST with its large aperture, low scattered light characteristics, and the capability to exploit the solar infrared spectrum will provide these critical measurements.

3. DETAILED SCIENCE REQUIREMENTS: EXAMPLE SCIENCE CASES

This section presents a number of the primary science cases driving the ATST design requirements. While other science cases will certainly arise, the ones listed span the critical functions the ATST must be able to perform.

3.1. HIGH-RESOLUTION OBSERVATIONS OF THE PHOTOSPHERE – CONVECTION AND MAGNETO-CONVECTION

These are the highest priority science drivers of the ATST representing an area where theoretical modeling capabilities have advanced tremendously, however, observational capabilities to test and drive these models are lacking.

3.1.1. Interaction of Weak and Strong Fields

Science questions:

- How are weak and strong fields generated?
- How do they disappear?
- Pattern of twist/helicity during flux emergence
- How do strong and weak fields interact? Do kilogauss flux tubes form by "convective collapse" from weaker fields?
- Do flux tubes ever dissolve into weaker fields?
- Does the weak-field component have a large-scale structure?
- How are shear fields structures formed at neutral lines?
- How does reconnection progress?

Observational requirements:

Spatial resolution:	0.”1 or 70 km at NIR wavelengths ; 0.”05 or 35km at visible wavelengths.
Time resolution:	10 sec - few minutes
Field-of-view:	60 arcsec (diffraction limited resolution limited to isoplanatic patch)
Spectral coverage:	visible, near IR
Spectral resolution:	1pm
Polarimetric sensitivity:	10^{-4} I_c (visible)

3.1.2. Flux emergence and disappearance

Science Questions:

Observational description of emerging flux

- Distributions of Field properties at emergence (strength, orientation, net unsigned flux)

- Active vs. Quiet regions
- Solar cycle dependence for quiet regions?
- Associated flows, foot point proper motions

Development of emerging flux in solar atmosphere

- Rate of rise (buoyancy and/or advection?)
- Process(es) of coalescence into kG flux tubes
- Process(es) of flux "cancellation"
- Evidence for "U-loop" expulsion into upper atmosphere (quantitative estimates)

Fate of emerged flux

- Quantitative flux history of plage, network
- Submergence?

Weak internetwork flux

- Influence of ephemeral regions
- Quantitative nature and history of "granular" fields (strong, very small scale, weak flux elements in intergranular lanes)
- Refine physical properties of remaining intergranular fields
- Define distribution functions of the intergranular flux

Observational Requirements:

<u>Angular resolution:</u>

Needs to be high enough to resolve flows around incipient flux tubes: 0.”05 or 35km is required. Higher resolution is desirable to reveal substructure in features undergoing collapse and intensification. *Goal: 0.”03 or 20km*

<u>Strehl ratio delivered by AO:</u>

High Strehl-ratios are required. Minimum requirement: S>0.3. Goal: S>0.7.

<u>Magnetic field strengths:</u>

Intrinsic field strengths for stronger fields (>200 G) should be determined within +/- 100G. This requirement is driven by the need to view changes in weak, horizontal fields as they emerge, migrate, and intensify.

<u>Magnetic field orientation:</u>

Orientation for stronger fields within +/-20 deg -- discern the approximate inclination to vertical

<u>Doppler velocity measurements:</u>

+/- 100 m/s: need 2-3 sigma detection of convective flows that are in equipartition with fields (flows typically few hundred m/s)

Time resolution:

10 sec: determined by the sound crossing time for small-scale collapsing elements: (0.1 arcsec @ 7 km/sec)

Field of view:

30-60 arcsec: large enough to comprise an actively emerging segment of a new active region, or to record the history of emergence events within one supergranular cell

Spectral coverage:

Simultaneous coverage of at least two lines (to measure field strength quantitatively), and IR lines (for weak field measurements in internetwork)

Spectral resolution:

2-3pm in visible lines will be adequate for this science goal.

Polarimetric sensitivity:

In the visible; 10^{-3} Ic for stronger fields, 10^{-4} Ic for weak internetwork fields. In the near IR these can be relaxed by a factor of 3.

3.1.3. Dynamics of Kilogauss Flux Tubes

Science Questions:

The main questions with respect to the dynamic behavior and structure of small scale kilo Gauss flux tubes that needs to be addressed with ATST are:

- Formation of photospheric flux concentration with field strength above the equipartition field strength and the dynamic interaction with the turbulent photospheric atmosphere.
- Observational verification of the process(es) that leads to kG flux concentration in the solar photosphere.
- Dynamic interaction of photospheric flux concentration with the turbulent granulation is essential in order to estimate the total energy flux that is transmitted / channeled by small scale flux tubes into the higher atmosphere. How are f.t. formed and how do they evolve?
- What is the lifetime of flux tubes (or sheets)?
- How do the flux tubes interact with turbulent flows in the photosphere?
- Why do filigree break up into "beads"?
- What is the internal and external flow structure?
- Why are not all flux tubes swept into vertices?
- What MHD waves are generated and what is their role in heating the upper solar atmosphere?

- How does the field vary through the Chromosphere?
- How do current sheets affect the structure of flux tubes?

Observational requirements:

Spatial resolution:

Typical spatial scales for dynamic effects seen in MHD flux tube models are in the order of tens of kilometers. Minimum requirement: 35 km.

Strehl ratio delivered by AO:

High Strehl-ratios are required. Minimum requirement: S>0.3. Goal: S>0.7.

Temporal resolution:

Horizontal motions:

Flux tube dynamics are expected to be closely related to granular evolution. Mean horizontal flows in the photosphere are of order 1 km/s. The maximum velocities can be much faster (sound speed: 7km/s). At 0.03" resolution (4m diffraction limit, 500nm) it takes ~ 20 sec for a structure to move across a resolution element. Time resolution required is: Minimum requirement: 20 sec

Simulation and observations show evidence for shock waves traveling along flux tubes. Vertical velocities of up to 20 km/s are verified. Typical formation height range of Stokes spectra in the photosphere is about 200-300 km . This requires a temporal resolution of <= 10 sec. Individual spectral features with a FWHM of <= 5pmare formed over a smaller atmospheric height range and require even better temporal resolution. Goal: A temporal resolution in the order of a second is desirable for this science goal.

Magnetic field strength:

kG flux tube formation from equipartition field (400-500G) requires precision of +/- 50G for intrinsic field strength measurements for each temporal and spatial data point.

Magnetic field orientation:

The clarification of the origin of Stokes profile asymmetries requires precise knowledge of field inclination in the range of +/- 10 deg.

Spectral resolution

Velocity measurements:

Doppler velocity in flux tubes and surroundings: +/- 25 m/s

Dispersion should be better or equal 10x the Doppler velocity in wavelength that we intend to resolve, i.e. 0.42 pm @ 500nm

Field of View:

Minimum: Isoplanatic patch. Goal: > 1 arcmin. Any spatial, spectral and/or temporal "scanning" needs to be completed within the required temporal resolution (10s).

<u>Spectral coverage:</u>

From near IR to near UV. Simultaneous multi-line spectropolarimetry to cover photospheric and lower chromospheric height range (see for example set of lines given in ATST technical Note on multiple Fabry-Perots TN 0001).

<u>Polarimetric sensitivity / Stray light:</u>

Critical: interference between neighboring magnetic features results in strong asymmetric profiles. 99% of polarimetric signal shall be contained within 0.”3. This requires very high Strehl ratios (see section 5.1.1)

Measurements of Doppler velocities in the immediate non-magnetic surrounding (a few 10 km) of a flux tube are required (Canopy effect). Such velocity measurements must not be contaminated from surrounding granular flows by stray light. Requirement: < 1% scattered light from surrounding photosphere (see tech note: TN 0002)

3.1.4. Internal Structure of Flux Tubes/ Irradiance Variations.

Science Questions

- What is the magnetic, thermodynamic, and velocity structure within kilogauss strength magnetic elements? Due to current resolution limitations, we observe magnetic elements as “point sources” convolved with the PSF, i.e. as homogenous structures in the solar atmosphere. MHD simulations and analytical considerations imply that there is considerable variation of basic properties at scales on the order of 10 km (ref: Cataneo, Nordlund, SanchezAlmeida). We need to measure magnetic field, temperature, density, pressure, chemical constituents at scales comparable to the peak of the turbulence power spectrum in the upper photosphere in order to understand the formation and evolution magnetic elements.

- How are these properties related to the photospheric flow field? It remains unclear how magnetic elements are formed. Both “shredding” of much larger scale structures such as pores and sunspots and local generation mechanisms (e.g. granular-scale turbulence) have been hypothesized (refs). Simulations show that larger magnetic structures such as micropores can exhibit complex vertical and horizontal flowfield patterns (Stein’s student). Properties of magnetic elements such as those listed above must be related to the local MHD flow field through specific measurements of vertical and horizontal flowspeeds at several depths in the photosphere in order to observe the interaction of granular flowfields with magnetic structures. The measurements must also be made with sufficient temporal resolution and cadence to resolve acoustic effects at the relevant scales.

- How do magnetic element properties vary with changes in flux concentration, flow field parameters, and location relative to larger magnetic structures such as pores and sunspots? A significant question remains whether there is any detectable difference between magnetic field concentrations in active regions (e.g. the constituents of plage) and those far from active regions (e.g. the constituents of the supergranular network). We need to measure the properties of magnetic elements over a wide range of conditions from the most active regions and even pre- and post-flare sites to the most quiet network regions at solar minimum. In order to avoid instrument calibration issues, these measurements must be made as closely in time to one another as practical. A related issue is whether statistical properties of magnetic elements vary over the solar cycle. Can we detect changes in properties as the cycle increases or decreases the active region concentration?

- What are the radiative transfer mechanisms responsible for the signature of magnetic elements in the UV, visible, and IR spectral regimes? The solar visible light irradiance varies by up to 0.1% in antiphase to the sunspot number over the course of the solar cycle (ref. Pap). The "excess" irradiance at sunspot maximum is believed to be due to irradiance from magnetic elements, both at the limb ("faculae") and on the disk ("plage"). The UV irradiance varies by much more than the visible. The IR signature of magnetic elements remains to be established. We need to understand the full spectral signature of magnetic elements from a fundamental physics standpoint in order to relate this signature to the solar irradiance as a whole. This involves measuring the thermodynamic properties listed above as well as the detailed chemistry of atomic and molecular atmospheric constituents within magnetic elements. With these measurements we can begin to construct the 3-D radiative transfer models necessary to understand solar irradiance as a function of magnetic field concentration.

- What is the acoustic environment within kilogauss magnetic concentrations? Which type of MHD and/or acoustic waves are important in the magnetic element energy balance? As the anchor points of larger chromospheric, transition region, and coronal magnetic structures, magnetic elements are the conduits through which flow and wave energy are transferred from the convection zone. We need to measure the local acoustic environment at scales comparable to the magnetic element size in order to understand the coupling of p-modes and surface waves into MHD waves in the "flux tubes" rising into the outer atmosphere. A related issue is how local concentrations of magnetic flux alter the transmission and reflection of the granular acoustic waves believed to be the source of p-modes (ref. Goody). Also, can we detect the signature of shock waves within or around magnetic elements? Shocks have long been hypothesized as a heating and/or acceleration mechanism for a variety of upper atmospheric phenomena such as jets and bright points.

Observational Requirements:

a. Imaging

Angular/spatial resolution:

0.03 arcsecond (25 km) at 500nm. Must resolve sub-structure of magnetic concentrations on the scale of the local inertial turbulent flow (ie. not at the dissipation scale). This scale would also sub-sample the intergranular downflow lanes by a factor of about 10-100, sufficient to link downflow events to specific structural changes in magnetic concentrations.

Field-of-view:

Minimum requirement: diffraction limited resolution within isoplanatic patch. Goal: several arcmin. Although magnetic elements themselves are sub-arcsecond in scale, need to simultaneously image a wide range of elements, e.g. within an active region and within the nearby supergranular network outside the active region.

Temporal cadence:

10 seconds**.** Must resolve sound speed travel times across the relevant spatial scales. Photospheric sound speed is approximately 7 km/sec.

Spectral coverage:

300–5000 nm. Need to make spectral line profile measurements from as far in the UV as possible from ground in order to address the irradiance question. Significance of upper range in the IR remains unclear – up to 5000 nm (5 microns) may be required (see 3.2.1 “Temperature and velocity structure of the photosphere”).

b. Magnetic field measurements

Polarimetric sensitivity:

I, V: 10^{-4}

U,Q: 10^{-3}. Small-scale fields predominantly vertical in the photosphere (ref. Sanchez-Almeida).

Field strength range:

0.1—6 kilogauss.

Spatial resolution:

0.03 arcseconds (25 km), Goal: 0.02 arcsec (at CaK).

Temporal resolution:

10 sec

Spectral coverage:

Visible and NIR. NUV lines for chromospheric magnetograms may also be desirable.

c. Velocity field measurements

Precision:

+/- 25 m/s (drives spectral resolution, see Technical Note TN 0002)

Speed range:

0.1—10 km/sec horizontal

0.1—50 km/sec vertical. Detect shocks in chromosphere.

Spatial resolution: 0.03 arcseconds (25 km):

Need to image the turbulent eddies at magnetic element formation scales.

Temporal resolution: 1 sec:

Resolve sound speed travel times at maximum resolution.

Cadence: 2—5 sec

Spectral coverage:

Visible. Variety of lines and line-wing measurements for sampling vertical and horizontal flowfields at a wide range of heights from temperature minimum to lower chromosphere.

d. Thermodynamic measurements

Spatial resolution: 0.03 arcsecond (25 km)

Temporal resolution: 1 sec

Spectral regions:

Atomic lines: formed in temperature minimum, photosphere, and chromosphere.

Continuum windows: in the blue, green, and red visible spectral regions. See PSPT instrument selection.

Molecular bandheads: CN 388.3 nm, CH 430.8 nm, CO 4.7 micron

Spectral resolution: R= ~ 200,000

3.1.5. Turbulent/Weak fields

Science Questions:

- What are the magnetic field strength, filling factor, spatial and temporal correlation length etc. distributions of the turbulent field?
- Are intranetwork fields the tip of the iceberg of turbulent fields?
- To what height in the atmosphere are these turbulent fields important?
- Do the turbulent field properties change with latitude, or are there other large-scale variations?
- Do the turbulent field properties change with the solar cycle?
- How is the turbulent field generated and destroyed?
- How does the turbulent field interact with the strong fields?

Observational Requirements:

Observing modes:

Observations with filter and spectrograph polarimeters in the visible, the near infrared (1.6 micron) and at 12 microns. It is desirable to operate visible and infrared instruments simultaneously. It is acceptable to not be able to operate two spectrographs simultaneously.

Spectral coverage:

Visible (particularly between 300 nm and 670 nm for Hanle observations (see section 3.1.6)) and near infrared (1.56 micron for Zeeman observations of weak fields), simultaneous 1.56 micron and 12 micron polarimetry.

Spectral resolution:

R>80,000 for Zeeman observations, R>150,000 for Hanle observations since scattering polarization sometimes produces very sharp spectral features such as in the Na D line cores.

Field of view:

2 arcmin is sufficient for Hanle effect measurements since scattering polarization is mostly restricted to areas close to the solar limb and Zeeman observations look at very small areas without the need to have simultaneous coverage of a large area.

Spatial resolution:

Zeeman effect observations: Minimum requirement is < 0.”1 for λ < 1.6 micron; diffraction limited for 12 micron. Goal: 0.”05 in the visible.

- Hanle effect observations: Trade offs between spatial resolution and polarimetric sensitivity will be necessary (see 3.1.6).

Polarimetric sensitivity and accuracy:

Both Hanle observations and Zeeman observations will require the highest possible sensitivity, which should be limited by the photon statistics only. A sensitivity of at least 10^{-5} should be reached in all four Stokes parameters. It is unlikely that Zeeman observations will be performed in Q and U because the linear polarization decreases much more rapidly with field strength than the circular polarization. Hanle observations will mostly focus on linear polarization, but cross-talk from circular polarization should be adequately suppressed by minimizing the instrumental cross-talk to less than 1% and correcting offline to less than 10^{-3}.

3.1.6. Hanle Effect Diagnostics

Science Questions:

- Light that emerges from a scattering medium is generally linearly polarized as long as the radiation field that is incident on the scattering particles is not isotropic. Since radiative scattering contributes to the formation of the Sun's spectrum and the incident radiation is anisotropic due to the limb darkening, the solar spectrum is linearly polarized even in the absence of magnetic fields. The linearly polarized spectrum is as rich in structures as the ordinary intensity spectrum but has an entirely different appearance and also different information contents. It has therefore been called ``the second solar spectrum". The scattering geometry that is related to the limb darkening leads to polarization that increases in magnitude as we approach the limb. Due to the small limb darkening in most of the visible spectrum the polarization amplitudes remain small, well below 1% for most spectral lines, however with a small number of notable resonance-line exceptions. Therefore only recently, with the development of highly sensitive imaging polarimeters, has it been possible to begin a systematic exploration of all parts of the rich second solar spectrum.
- The term Hanle effect represents the totality of ways in which the scattering polarization can be modified by magnetic fields. The Zeeman and Hanle effects are highly complementary to each other because they respond to magnetic fields in very different parameter regimes. While the magnitude of the Zeeman-effect polarization depends on the ratio between the Zeeman splitting and the Doppler line width, the Hanle effect depends on the ratio between the Zeeman splitting and the damping width (or inverse life time) of the relevant atomic levels. The Hanle effect can relate to atomic polarization of the upper or the lower level of a transition. For upper-level Hanle effect the magnetic-field sensitivity range is typically 1--100 G, while for lower-level Hanle effect it is 2--3 orders of magnitude smaller (in the milligauss regime). As the Hanle and Zeeman effects have different symmetry properties, cancellation effects that occur for the Zeeman effect

may not occur for the Hanle effect. For instance, a spatially unresolved turbulent magnetic field with an isotropic distribution of field vectors is invisible to the Zeeman effect due to cancellation of the opposite polarity contributions, while these contributions do not cancel for the Hanle effect. The Hanle effect has therefore in the past enabled the detection of the existence of such a turbulent solar field.

For the diagnostic use of the Hanle effect the solar UV is the spectral region of choice, for two main reasons:

(1) Since the limb darkening increases steeply with decreasing wavelength, the amplitudes of the scattering polarization increase correspondingly, such that the effects appear amplified.

(2) The UV is much richer in resonance lines suitable for Hanle diagnostics than higher-wavelength regions.

To resolve ambiguities in the complex interpretations of Hanle observations, one needs to combine observations in a set of well-chosen lines with different sensitivities to the Hanle effect but with otherwise similar formation properties. The UV offers much better choices. High-sensitivity imaging Stokes polarimetry in the UV has recently been successfully implemented, allowing us to explore the Hanle effect down to the atmospheric cut-off near 300 nm. **For Hanle-effect diagnostics it is important that ATST allows high-sensitivity imaging spectro-polarimetry down to the atmospheric cut-off.**

Most of the early use (in the 1970s) of the Hanle effect was for the diagnostics of magnetic fields in prominences with the He I D_3 line, which had the advantage of large polarization signals (a few percent), and a well defined incident radiation field on an optically thin scattering medium, removing the need for complex radiative transfer to interpret the observations. Off-limb observations of prominences and the solar chromosphere will remain important applications of the Hanle effect in the ATST era, but the on-disk observations offer a much richer variety in the possible observational uses of the Hanle effect. In particular one wants to explore the spatial structuring and temporal variability of the weak and turbulent magnetic fields at different heights in the solar atmosphere, and have good determinations of the horizontal component of chromospheric magnetic fields. The best signal strength on the disk is found within a limb zone, implying that most Hanle observations on the disk will be made within about **30 arcsec from the limb,** although the width of the limb zone depends on the trade-off with the polarimetric S/N ratio. There is however a possibility of observing the Hanle effect also at disk center, and therefore also over a large portion of the disk, since for horizontal magnetic fields the Hanle effect can generate polarization in {\it forward} scattering, when the non-magnetic scattering polarization is zero. This theoretical possibility, which would be most interesting for horizontal chromospheric magnetic fields (which are too weak to be seen by the transverse Zeeman effect) has however yet to be explored.

The main implications of the Hanle diagnostics for the ATST instrument requirements are the following:

Observational Requirements:

Spectral Coverage:

Full polarimetric access to the UV, down to the atmospheric cut-off near 300 nm.

Polarimetric Sensitivity:

The relative polarimetric sensitivity should only be limited by photon statistics down to a level of at least 10^{-5} Ic. It means that the random noise in the Stokes images should be smaller than this value when sufficient trade-off with spatial and temporal resolutions are made to achieve the required photon statistics.

Scattered Light:

For off-limb observations of prominences and the chromosphere it is critical to have minimal instrumental scattered light, a requirement that is shared with the coronal observations (see section: 3.2.5.)

3.1.7. Magnetoconvection in Sunspots

Science Questions:

- Origin and dynamics of umbral dots: Oscillatory convection vs. field free plumes
- Sub-photospheric structure of Sunspots
- 3-D structure of sunspots?
- Origin and dynamics of umbral and penumbral oscillations
- Oscillatory convection: Verify model predictions
- Origin and dynamics of penumbral finestructure
- What is the size distribution of penumbral filaments (MISMA?)
- MHD waves in sunspots: verify model predictions
- Physics of photospheric and chromospheric Evershed effect: Verify model predictions!
- Are there oscillations of the umbral magnetic field strength?

Observational requirements:

FOV:

Minimum requirement: 1 arcmin, Goal: 5 arcmin

Resolution:

Minimum: diffraction limited within isoplanatic patch. Goal: diffraction limited over >1 arc min. High Strehl ratios S >0.3 are needed.

Temporal resolution:

10 sec –30 sec

Temporal coverage:

Minimum: 30 min Goal: several hours

Wavelength Coverage:

- Simultaneous observations of photospheric, chromospheric, and possible coronal lines is required.
- Simultaneous measurements of velocity, vector magnetic field and other physical parameters such as continuum- and line core intensity and temperature. Photospheric velocity: g=0 lines, e.g., FeI 5691, FeI 5576, FeI 5434. Chromospheric velocity: e.g., H-alpha, NaD2, MgB1, He-10830.
- Photospheric magnetic field field: FeI 6302, FeI 5250, FeI 1.56 micron. Upper photosphere: Mg lines at 12 micron.

  Chromospheric magnetic field: e.g.: HeI 1.0830 micron, CaK

  Coronal magnetic field: He 1.0747, Si 3.9 micron.

Spectral resolution:

1-2pm, R=200000-500000 will suffice for most cases.

Polarimetric Sensitivity and Accuracy:

10^{-3} photosphere. 10^{-4} chromosphere.

3.1.8. Generation of Acoustic Oscillations

Science Questions:

- How are p-mode oscillations excited?
- Are acoustic events in intergranular lanes the only source?
- Why are there localized events (in space and time)?
- Gain detailed understanding of “acoustic events”. Verify detailed model predictions.
- Are acoustic events responsible for chromospheric heating? Connection between events and CaK bright points?
- How does the magnetic field affect the generation of acoustic power?

Observational Requirements:

FOV:

Minimum requirement: 1 arcmin, Goal: 3 arcmin

Spatial resolution:

< 0.”05 or 35km to resolve substructure in intergranular lanes.

Spectral resolution:

1-2pm, R=200000-500000

Spectral Coverage:

Simultaneous:

- Observations of several photospheric and chromospheric lines. E.g., FeI 5576, FeI 5434, CaK2V (0.5 A bandwidth),
- Observations of velocity and magnetic field (e.g. FeI 6302, FeI 5250)
- Spectrograph and narrowband filter observations

Temporal resolution:

10 sec –30 sec, spectral or spatial scanning has to be completed with this time.

Temporal coverage:

Minimum: 30 min

Goal: several hours

3.2. STRUCTURE AND DYNAMICS OF THE UPPER ATMOSPHERE

3.2.1. Temperature and Velocity Structure of the Photosphere and Chromosphere.

Science questions:

- How accurate are the hydrodynamic simulations of the solar convection?

  We only observe the uppermost layer of the solar convection through the shape, form, and dynamics of the granulation. We need to verify the predictions of simulations to a high degree of accuracy in terms of the spectrum of spatial and temporal scales, and temperature variations.

- Related questions are what is the average temperature as function of height in the quiet Sun, and what are the fluctuations as a function of height. How well can we describe the convective atmosphere in terms of simple models, like one-dimensional hydrostatic models, two-stream models, and mixing length parametrization, that are used in modeling stellar structure and evolution.

- An important quantity with regard to (solar and stellar) abundance determination is the concentration of molecular species. The question is whether chemical reaction times at the formation heights of the employed molecular lines are faster than hydrodynamic evolution time scales, comparable, or slower. In the latter two cases the molecular concentrations cannot be assumed to be in equilibrium.

- A related question is the formation height of the strongest CO (and OH) lines that show such low temperatures towards the limb. Since LTE excitation holds in these lines, the derived temperatures must be real. It is not clear where they occur. Establishing this formation height would have far reaching implications for our ideas on chromospheric structure (for instance spatial inhomogeneities versus temporal variations).

- How do effects of non-LTE ionization affect temperature and abundance measurements? Departures from equilibrium lead to erroneous conclusions about element concentrations and/or line formation heights when observed spectra are interpreted with the assumption of LTE.

- What are spicules observed at the solar limb?

Observational requirements:

<u>Spectral coverage:</u>

0.38 to 5 micron. Should be able to observe several (up to 4) lines strictly simultaneously, in widely different wavelength ranges to cover different heights. For instance obtain spectra of photospheric atomic lines and molecular lines at the same time to get a handle on molecular formation times. This includes the ability to observe in the fundamental CO vibration rotation lines at 4.7 micron together with optical lines in the blue, like the CaII H and K lines, or even the CN band head at 388.3 nm

<u>Angular resolution:</u>

0.03 arcsec at 500 nm. Hydrodynamic simulations indicate that spatial scales of down to 25 km are relevant. Below that the predicted spectra change little. This corresponds to 0".03. In the 4.7 micron region we require at least 0".3 to resolve the inter-granular lanes and distinguish centers of granular overshoot.

<u>Temporal resolution:</u>

1 second. For fixed slit a 5 second cadence corresponds to a vertical distance of about a quarter of a density scale height at approximately the sound speed. This is only twice the Nyquist frequency for a height resolution of a scale height. For spectra-spectroheliograms the requirements are more stringent. At a 1 second cadence and a 0".1 step size only a 3" strip can be collected in 30 seconds, which is a typical time on which changes in the granulation and 3-5 minute oscillations occur. Repetitive scans can be at this cadence with a temporal resolution of 30 seconds for the scanned area, but this already results in under-sampling of height.

<u>Field of view:</u>

1 arcmin. Needs to be large enough to sample the spatial scale of the 5-minute oscillations, which is typically 10-15". So one arcmin would be sufficient.

<u>Spectral resolution:</u>

R= 200,000. A spectral resolution of about 200,000 is needed to accurately measure temperature differences in spectral lines. This corresponds to 2-3 pm in the visible and 24 pm at 4.7 micron. A typical CO line is 100-200 pm wide. If the spectral broadening is Gaussian with a FWHM of 24 pm the line core fills in with a maximum relative change of 1-2%. This figure is 5% (comparable to the temperature variations to be measured) when the resolution is only 100,000. In both the optical and infrared this resolution should also be sufficient for accurate Doppler measurements.

<u>Scattered light:</u>

Less than 1% spectrally. Scattered light in the spectrograph should be not more than 1-2%. Scattered light in the imaging optics is less important as the granular contrast is only 20-30% in the optical and less in the infrared.

3.2.2. Chromospheric Heating and Dynamics.

Science Questions:

- Network heating
  - Relate photospheric flows, foot point proper motions to the chromosphere
    - Active vs. quiet regions
  - Sources and role of high frequency (> 10 mHz) wave power
- Internetwork heating
  - Low frequency (< 10 mHz) oscillations
  - Sources of high frequency (> 10 mHz) acoustic power
  - Suppression of heating by magnetic fields in shadows
  - Canopy interactions
  - Cool (CO) vs hot (Ca II) components
- Chromosphere as the base of the corona
  - Source of mass, momentum and energy for the corona
  - FIP effect (element fractionation)
  - Spicule origins
- Sunspot oscillations
  - Study of MHD modes
- Expansion of flux tubes into the canopy
  - Study change in plasma beta regime (>1 to < 1)
  - Searches for MHD mode coupling

Observational Requirements:

<u>Spectral coverage:</u>

Strictly simultaneous measurements of prime photospheric magnetically sensitive lines and chromospheric lines are needed. At least one of 630nm Fe lines and 1.56 micron Fe I lines should be measured with one of Ca II H or (393 nm), Na I D, H alpha, one or more Ca II IR triplet lines, He I 10830, CO vibration-rotation bands near 2.3 (Δ v=2) and 4.7 (Δ v=1) microns, chromospheric iron lines. Some magnetic sensitivity in the chromosphere is highly desirable.

Angular resolution:

Needs to be high enough to resolve flows driving network and internetwork flux tubes: 0.1 arcsec is minimum requirement. Higher resolution is very desirable to highlight granular dynamics as sources of high frequency acoustic power, and to measure dynamics of weak intergranular fields.

Magnetic field strengths:

Intrinsic field strengths for stronger fields (>200 G) should be determined within +/- 100G. This requirement is driven by the need to view changes in weak, horizontal fields as they emerge, migrate, and intensify.

Magnetic field orientation:

Orientation for stronger fields within +/-20 deg -- discern the approximate inclination to vertical

Doppler velocity measurements:

+/- 100 m/s: need 2-3 sigma detection of convective flows that are in equipartition with fields (flows typically few hundred m/s), as drivers of Poynting flux into higher layers.

Time resolution:

8 sec: fixed by the sound crossing time for small-scale collapsing elements and over photon path lengths/ scale heights (120 km) (0.1 arcsec @ 7 km/sec), at Nyquist limit for high frequency waves.

Field of view:

30-60 arcsec. Large enough to record several the ~8 arcsec patches of 3 minute oscillations, to investigate non-vertical (canopy) connections between photosphere and chromosphere, and rosettes of spicules.

Spectral resolution:

2-3pm in visible lines should be adequate

Polarimetric sensitivity:

In the visible; 10^{-3} Ic for stronger fields, 10^{-4} Ic for weak internetwork fields. Near IR these can be relaxed by a factor of 3.

Scattered light:

Sunspots demand that telescope PSF, 10-20 arcseconds from penumbra be less than a 10 % of the umbral intensity at all wavelengths including Ca II K. For a dark umbra (0.1I_photosphere) this implies that scattered light from surrounding photosphere must be < 1% (see Technical Note TN 0001).

Other:

Integral-field spectroscopy is ideal, but some of the goals can be met with filter instruments (fast cadence) or rastering of slits (slow cadence). Connections to the corona / transition region will require use of space-based instruments.

3.2.3. Spicules

Science questions:

- how are spicules formed?
- can very high resolution (sub-arcsecond) intensity observations yield clues to the formation mechanisms? (internal motions, for example)
- can we get reliable magnetic data from Stokes spectra of spicules?
- if so, does spicule morphology/dynamics reflect field-aligned structures?
- what is relationship with the underlying magnetic network, with H alpha mottles seen on disk?
- how important are they for coronal physics?

Observational requirements:

Some properties of typical spicules are assumed, taken from Beckers' (1972) review. It's useful first to note that spicules live just 5-20 minutes, they are between 400-1500 km across, and typically extend 6500-9500 km in projected height.

The table gives typical intensities at 6000 km above limb, erg/cm^2/s/sr/A, taken from Beckers (1972). Individual spicules vary greatly from these numbers:

Line	**λ**	**disk**	**dark**	**line**	**line/(disk*dark)**
H alpha	6563.0	2.4e+06	4.8e-01	2.0e+05	0.17
H beta	4861.0	2.9e+06	3.3e-01	1.5e+05	0.16
D3	5875.0	2.7e+06	4.3e-01	2.0e+04	0.02
He	10830.0	9.4e+05	6.4e-01	6.0e+04	0.10
Ca II K	3933.0	2.6e+06	2.1e-01	5.0e+04	0.09

nb: 1. "disk" is simply planck function at 5900K
2. "dark" is Allen's continuum limb darkening function, evaluated 5 arcseconds inside the limb (1=disk center)
3. spicules are only a factor of 2 or so brighter at their "base" (between 0 and 2 arcseconds above the limb).

Spatial resolution:

Multi-spectral observations with 1" or so resolution indicate unresolved thermal structure, e.g. in internal rotational motions. The highest possible resolution compatible with the low spicule intensities and high disk scattered light seems warranted. Pixel sizes 10 times the area of those used for disk observations will yield the same integration time, so 0.3 arc seconds would seem a reasonable requirement, 0.1 arcseconds a good goal for filter work/ spectroscopy (probably not spectro-polarimetry).

Temporal resolution:

Spicules have a lifetime of 5-20 minutes, but various observations indicate the presence of smaller structures unresolved at 1" resolution. Coupled with 25 km/s or higher proper motions and Doppler velocities this indicates that higher cadences are needed, probably of 10 seconds or so if 0.3" spatial resolution is chosen. Also, proposed mechanisms usually invoke dynamics on small spatial scales with corresponding smaller timescales.

Magnetic field strength and orientation:

It's not possible to set this parameter at present- simply one should get the highest accuracy Stokes parameters possible. Zeeman effect will be very challenging but potentially very useful analogous to the coronal problem, but with potentially more damaging stray light issues being just arc seconds from the limb. Spicule lines are expected to be polarized and such measurements will be interesting in themselves (e.g., radiative vs. collisional excitation rates will follow from linear polarization degree, orientation of magnetic field can be checked against the observed proper motions to test various propositions for spicule acceleration/ formation). Hanle effect is unexplored but also requires high sensitivity.

Spectral resolution:

There is a class of narrow-lined spicules (Beckers' type II) with FWHM of 10 km/s, but most spicules are a factor of 3 wider. Thus, R=100,000 is needed to at least partly resolve the narrow profiles. Furthermore, some of the most well known and interesting spicule properties have been derived from tunable filter instruments, scanning across the H alpha line profile with spectral resolutions of at least 20,000.

Field of view:

Spicules come in groups (Lippincott 1957) associated with e.g polar plumes ("wheat fields") of size 140,000 km or supergranules ("porcupines"), of size 5000 km and separated by 25,000 km. Thus 30 arcseconds along the limb is a minimum, 180 arc seconds will capture the wheat fields. Spicules at visible wavelengths do not extend beyond 20 arcseconds above the limb, "macro-spicules" seen in EUV transition region lines can extend much higher,80 arcseconds or so. The nominal 180x180 arcseconds ATST FOV is therefore more than adequate.

Spectral coverage:

Beckers (1972) notes that, when available, near-simultaneous data in different lines can reveal intriguing information on the spatially unresolved structure within spicules. For example, some correlations of linewidths of He I vs Ca II suggested that things like temperature and Doppler velocity gradients across the spicule cross sections could be inferred. It seems that multi-wavelengths will be important for spicule observations with ATST, such that H alpha, Ca II K, and He I 10830 should be observed simultaneously. There may be other lines in the ATST range (e.g. Mg I b) but these will certainly be weaker and more challenging to work with.

Polarimetric sensitivity:

This should be as high as possible compatible with the short integration times (10s or less), low light levels (0.1 x limb intensity and less), high stray light background.

Stray light:

At 6000 km (8 arcseconds) above the limb, the table shows that we need disk scattered light less than 1% of the limb intensity for a signal to noise ratio of 10:1 for intensity measurements of most lines. For polarimetry the requirements are more stringent commensurate with the (as yet unknown) fractional polarization. Simulations would be needed to address this point as well as

Other:

Can AO work well at the limb? Maybe spicules in H alpha are good enough in themselves. AO will be critical for much of the spicule science.

Spicules are an obvious target for coordinated space observations in the EUV (e.g. He II 30.4 nm emission with SDO).

3.2.4. Prominence Formations and Eruption.

Prominences (a.k.a. filaments) are located in the corona but possess temperatures a hundred times lower and densities a hundred times greater than coronal values. Many important questions about prominences remain unanswered. In the following we describe how ATST observations can help answer these questions.

Science questions

- Prominence structure:
  - What is the magnetic structure of a prominence (filament) and surrounding coronal cavity?
  - What is the thermodynamic structure of filament threads?
  - How is the filament plasma supported against gravity?
  - How is the plasma heated?
  - How is mass injected into filaments?
  - What is the nature of flows and waves within filaments?
  - What is the nature of the "barbs" that protrude from the sides of a filament?
- Formation of prominence magnetic field:
  - How is the magnetic structure of a prominence formed?
  - What is the role of photospheric flux emergence and cancellation?
  - What causes the hemispheric pattern of prominence axial fields (dextral in the North, sinistral in the South)?
  - What is association with non-potential configurations of the photosphere?
- Prominence eruption:
  - What causes filaments to erupt? Is magnetic reconnection involved?
  - What is the nature of the heating in erupting filaments?

Observational requirements

a. Prominence structure

To answer questions about the temperature, density and velocity structure of filaments and prominences will require high-resolution observations of various types of filaments in active regions and on the quiet sun.

Wavelength coverage:

These observations will require near-simultaneous narrowband imaging with in several of the following spectral lines: H-alpha, H-beta, He 587.6 nm, He 1083 nm, Na D, CaII H&K, CaII 854.2 nm.

- FOV:

at least 3 arcmin.

Spatial resolution:

For imaging at 656.3 nm the required spatial resolution is 0”.05 for disk filaments and 0”.1 for prominences above the limb; the latter may require using H-alpha prominences for AO wavefront sensing.

Spectral Resolution:

A passband with FWHM of 5 pm is required. The passband needs to be stepped across the line profile in 3 to 10 steps (max. range +/- 200 pm) with an overall cadence of 5 to 20 seconds. The purpose is to capture high-velocity flows that may be associated with reconnection events in or around filaments.

We will also need simultaneous images and spectra in the above-mentioned spectral lines. The spectra are needed to obtain accurate measurements of Doppler shift and spectral line broadening inside filaments. A spatial resolution of the spectrograph of 0.1 arcsec and spectral resolution of R=200,000 are required.

Co-registration:

The spatial position of the spectra relative to the images need to be known to +/- 0”.03 (e.g., by rastering the slit and cross-correlating imaging and spectral data). Since filament threads evolve rapidly, the cadence of such spectra should be a few seconds. Medium resolution spectra (50,000) are needed to measure Stark broadening in Balmer lines, which provides information about electron densities in filaments. The IR spectrum of filaments should also be observed.

To determine the magnetic structure of prominences requires measurements of polarization in hydrogen and helium lines on the solar disk and above the limb, using spectra with spectral resolution of about 130,000 and spatial resolution of 0”.3 .

Polarimetric Sensitivity:

For Zeeman measurements in quiescent filaments we need to be able to measure longitudinal fields of 5 - 10 Mx/cm^2 using H-alpha or H-beta; this requires a polarimetric sensitivity of at least 1.E-4 in Stokes V/I because of the broad line profiles of the hydrogen lines and the relatively small Lande g-factor (an on-disk Stokes profile calculation for H-alpha by Han Uitenbroek shows that a 5 G fully resolved vertical field leads to a Stokes V signal with a peak amplitude of $1.5 \cdot 10^{-4}$). Hanle measurements in prominences will use He I 587.6 nm (He D3), which is optically thin and therefore relatively easy to interpret (see Leroy 1989). The required polarimetric sensitivity for such measurements is $1 \cdot 10^{-3}$ in Stokes Q/I and U/I, where I is the He I 587.6 intensity in the prominence, which is only a few percent of the disk center intensity (TBC). Both Zeeman and Hanle measurements will require dwell times ~ 10 seconds to obtain this polarimetric sensitivity.

Scattered Light:

The Hanle measurements require scattered light less than 10^{-4} of disk intensity at heights 10-100 arcsec above the limb.

b. Active region filament

For active region filaments we need to measure magnetic fields inside the filament using the Zeeman effect in the above-mentioned hydrogen and helium lines. This requires full Stokes profiles with spectral resolution of 130,000 and spatial resolution of 0.5 arcsec. The required polarimetric sensitivity is $1 \cdot 10^{-4}$. We will also simultaneously measure the photospheric vector field, so that we can compare the observed filament fields with those predicted by force-free extrapolations.

3.2.4.1. Formation of prominence magnetic field

- Prominences are located in filament channels, regions where the chromospheric fibrils are aligned with the polarity inversion line and the magnetic field has a strong axial component. To understand how these magnetic structures are formed, we need observations of the underlying photospheric and chromospheric magnetic fields. We need to accurately measure the fluxes of magnetic elements within the filament channel. This requires accurate flux accounting in order to follow the magnetic flux over long periods of time (several hours) and to measure slow but steady flux cancellation. Magnetic flux concentrations of 10^{18} Mx should be measured with an accuracy of 10%. We also need to measure the proper motions of magnetic features to detect shear flows along the channel and converging flows perpendicular to the channel.

- A closely related goal is to measure the horizontal fields in emerging and canceling magnetic "bipoles" in order to determine how much horizontal field is injected into or removed from the corona above.

- Search for large-scale patterns in the orientations of horizontal fields in emerging and canceling bipoles. Such data will also allow us to determine whether canceling features represent the submergence of Omega-loops or the emergence of U-loops. Information about vertical flows would also be useful for this purpose.

Observational requirements:

Spatial resolution:	0.5 arcsec
Magnetic Field (Flux):	The horizontal field should be mapped with an accuracy of +/- 50 Mx/cm^2

Temporal resolution:	cadence of once per minute.
Polarimetric sensitivity:	Visible, NIR: $1\cdot10^{-3}$
FOV:	Minimum: 3 arcmin

3.2.4.2. *Filament eruptions*

TBD.

3.2.5. Coronal magnetic fields.

Science requirements for coronal observations are not as easy to define as those for photospheric observations because they present very different challenges. Some of the requirements are likely to change as we gain experience with these techniques, for example at the prototype SOLAR-C telescope. These uncertain requirements are flagged below with "*".

Observations from Lin et al (2000) provided the first polarization measurements using the 1075nm Fe XIII of the coronal magnetic field at one pixel in the solar corona. Several science cases listed below require scanning large regions of the corona with sensitivity approaching that reached by Lin et al. The estimated one-sigma measurement errors for “reasonable” instrument and site background levels are 30 +30/-15 Gauss for a one arcsec^2 pixel for a one second exposure. This calculation assumes a rather poor efficiency for the spectrograph instrument (1%) and a single slit rather than a multi-slit or fiber design.

To address the science questions below a 2x2 arcsecond pixel size is assumed, reducing the 1 Σ error to 15 +15/-7 Gauss. To achieve 1/3 of the sensitivity reached by the Lin et al measurement the one-sigma value must be lowered to 0.3 Gauss, implying an increase in the collected photons by a factor of 2500. This can be achieved with a 42 minute integration.

However for scanning a region of the corona a cadence of a few minutes is desired. If we boost the acceptable one-sigma value to 1 Gauss, we must increase the collected photon flux by only 225. To scan a 180 arcsec FOV with 2 arcsec slit size required 90 steps, and to achieve a 10 minute cadence this allows only 7 seconds integration per step. This requires a flux increase of 32 through the spectrograph instrument, pushing the required efficiency up to 32%. These values assume active region loop coronal intensities and the measurement noise will certainly increase in regions of the corona where the coronal line emission is less than 40 millionths.

Science Questions:

- Pre- and post-CME field configurations:
- what configurations lead to CME ejection
  - what is the change in magnetic configurations accompanying CMEs?
  - direct tests of CME, or plasmoid, etc. acceleration models
- Pre- and post-flare loop systems:
  - what configurations lead to flares?
  - what is the change in magnetic configurations accompanying flares?

- Dynamics of coronal magnetic field during:
  - filament/prominence eruptions
  - flaring active regions
  - CME events
- Coronal loops:
  - are loops all "flux tubes" or are some separators or current sheets?
  - how much twist (free energy) is in the field?
- Prominence cavity structure:
  - direct test of magnetic models of prominence cavities
- Extrapolations:
  - how good are extrapolation techniques (force-free, minimum current,...)?
- Wave phenomena:
  - direct detection of low-frequency (< 1Hz) waves in the corona

Observational Requirements:

Spectral coverage:

Fe XIII 1.0747, 1.0798, Mg VIII 3.028 and Si IX 3.9346 microns are prime candidates. He I D3 (0.5876) and He I 1.0830 should be used for Hanle and Zeeman measurements of prominence magnetic fields.

Field of view:

Minimum requirement: 3 arcmin. Goal: Coronal structures of up to 5 arcmin should be targets.

Spectral resolution:

Filtergrams with R=lambda/(delta-lambda) = 10000 is a minimum, where delta-lambda is FWHM. R=100000 is required for IR spectrographs (FWHM = 3 km/s).

Angular resolution:

Stokes V measurements (LOS field strength) are photon-starved, IQU are not. V measurements should not be made even close to the diffraction limit (0.06" for 4m aperture at 1 micron). TRACE images (1" resolution, 0.5" pixels) indicate that 2x2 arcsecond pixels can resolve structure in the Fe XII emitting plasmas. However, high-resolution coronal imaging in Stokes IQU will be very interesting. With 4 meter aperture, ATST can try to get beyond the TRACE limit. 0.5" resolution should be an initial goal.

Off-limb pointing capability:

3-4 micron measurements might be possible as close as 1.05 radii. So 1.05-1.35 radii should be the minimum requirement. A low angular resolution, larger FOV (1 solar radius?) mode should at least be considered. With a 1 solar radius FOV, then we need to be able to point to 1.5 solar radius.

Sky brightness:

A sky brightness value of 25 millionths at 1.1 solar radii at 1075nm is assumed. A larger background decreases the spectral signal to noise ratio and increases the required exposure time. A total background (sky plus instrument) of 50 millionths is assumed.

Instrumental scattered light:

A combined instrumental background (dust and roughness scattering) value of 25 millionths at 1.1 solar radii at 1075nm is assumed. A larger background decreases the spectral signal to noise ratio and increases the required exposure time. A total background (sky plus instrument) of 50 millionths is assumed.

Doppler velocity measurements:

+/- 1 km/s will be useful to follow 3D magnetic field orientations from proper motions and Doppler shifts combined. A target of a few hundred m/s seems reasonable, and is compatible with spectral PSF with a FWHM of 3 km/s.

Imaging spectro-polarimetry capability (filtergrams or fiber-fed spectrographs):

A 2-3" pixel resolution imaging spectro-polarimeter system covering 300"x300" FOV should be a good start.

Time resolution (Stokes IQU):

Intensity and linear polarization resonance scattering measurements can all be performed much faster than V, provided the I->QU cross-talk is handled effectively, with integration times of a few seconds depending on the angular binning.

Time resolution (Stokes V):

Limited by photon counting statistic of faint corona and variable background emission in I+X, I-X, where X includes QUV (QU are needed to determine the QU -> cross-talk). With 2x2 arcsecond pixels, at least a 1.3 hour integration is needed for Fe XIII under typical conditions at 1.1 solar radius above the limb to get 1-sigma for a weak, 0.3 G field strength, allowing only for photon counting statistics. 200 seconds is needed for a 1-sigma detection of a 3G field.

Magnetic field sensitivity:

No specification possible- it depends very strongly on the wavelength, sky conditions, and limb distance.

Cross-talk:

Strictly simultaneous measurements must be taken in all four Stokes states. A slow chopping technique, which moves orthogonal Stokes measurements to different detectors to remove gain variation systematics is also desired.

Polarimetric stability:

> Requirement: no more than 5·10-4 for all Mueller matrix elements within 15 minutes; goal of 1·10-5 for all Mueller matrix elements over the duration of (2 hours).

3.2.6. Coronal Plasmoid Search

Small packets of coronal plasma, "plasmoids" have been predicted by coronal models do have sizes near 250 km and to play a major role in the mass flux of the solar wind (Mullan 1990). Observations during the 1991 eclipse using the 3.6m CFH telescope observed a plasmoid feature with a size of about 1500 km and internal structure at the 400km seeing limit of the data (Delannee et al.1998, Zhukov et al. 2000). The feature was seen during the short 210 seconds of totality as it moved across the corona at a mean height of 1.13Rsun. The feature was observed in white light but thought to have a cool temperature near 10^4 K.

For a 1 second exposure with 1x1 arcsec pixels the ATST is expected to achieve a S/N ratio of 1070 in the 2A wide Fe XIII emission line where the line has a brightness of 40 millionths of the disk center brightness. Reducing this spatial scale to 0.1 pixels decreases the flux by a factor of 100. Further, making the exposure time 10 milliseconds to freeze the seeing now reduces the flux by a total factor of 10^4. This reduces the S/N ratio to 11; if a coronal plasmoid is bright in Fe XIII then direct imaging in this line with ATST with high spatial dispersion with short exposures should reveal coronal plasmoids. The 3 sigma limit is reached at an Fe XIII brightness of 3 millionths; if coronal plasmoids are at least this bright then ATST direct imaging (with simultaneous continuum subtraction) should reveal plasmoids. However, since previous observations suggest plasmoids are cool, another option is to use the He I 1083nm emission line. This line is much brighter than the coronal Fe XIII emission as the transition is not a forbidden transition, and the 1083nm emission is often seen at levels of several thousand millionths of the disk center intensity in prominences off the limb. As the line is also about a factor of 10 more narrow than the Fe XIII line, the 3 sigma limit detection limit in He I would be about 10 millionths disk center intensity.

If coronal plasmoids are faint in emission lines a different detection technique is required which could employ broadband polarization imaging without a spectrograph. Assuming 40% transmission through the polarizing element, and a plasmoid brightness of 0.1 millionths, and integrating over a 50nm filter pass band near 1 micron with a background brightness of 50 millionths results in a 2.4 sigma detection of the plasmoid.

The source of these plasmoids is unknown; they may be related to spicules or macrospicules. For this reason plasmoid observations should be made in conjunction with limb spicule observations. If these plasmoids are common and observable, they will help to trace out the solar wind velocity and acceleration properties at limb heights below the $2R_{sun}$ limit of current space-based results (Lewis and Simnett, 2002). For these reasons limb pointing from a lower limit of 1.03 to the upper limit of the ATST pointing is desired.

Delannee, C., Koutchmy, S., Veselovsky, I.S., Zukhov, A.N., 1998, A&A, v329, p1111

Lewis, D.J. and Simnett, G.M., 2002, MNRAS v333 p969.

Mullan, D.J. 1990, A&A, v232 p520

Zuhkov, A.N., Veselovsky, I.S., Koutchmy, S., Delannee, C. 2000, A&A, v353, p786.

Main Science Questions:

- What is the mass flux carried by coronal plasmoids?
- What is the velocity profile of plasmoids as a function of height? Do the plasmoids accelerate as expected by solar wind models?
- What is the internal structure of a plasmoid?
- How do plasmoids interact with the solar magnetic field?

Observational Requirements:

Spectral coverage:

Fe XIII 1075nm, Fe XIII 1080nm, Si X 1431nm and other coronal emission lines will provide windows to seek plasmoids as will the cool emission line of He I at 1083nm and large bandpass polarized continuum measurements with 50nm or greater of the spectrum observed near 1000nm.

Field of view:

The entire FOV of the ATST must be accessible. The ATST limb height pointing requirements will depend upon the FOV used.

Spectral resolution:

Intensity measurements integrated over the entire coronal emission line (0.2nm width at 1000nm) are required with strictly simultaneous measurements in the nearby continuum. There must be at least two continuum channels to measure the background to attain the signal to noise levels discussed here.

Angular resolution:

An 0.1 arcsecond pixel is desired; the spatial size of plasmoids is expected to be 2 arcseconds or less and they are known to have internal structure on the scale of 0.5 arcseconds. Typical observing sequences will use many rapid exposure frames and frame selection to chose the best seeing frames.

Off-limb pointing capability:

Ability to observe from 1.03 to at least 1.5 solar radii and possibly 2.0 solar radii.

Sky brightness:

A target value is 25 millionths of disk center brightness. The total background intensity target value is below 50 millionths.

Instrumental scattered light:

A target value is 23 millionths of disk center brightness from dust and mirror roughness. The total background intensity target value is below 50 millionths.

Time resolution:

A very short exposure time is required to freeze seeing to achieve the desired spatial resolution. A target exposure time is 10 milliseconds. Calibration with disk light is required and so adjusting the primary mirror shape to reduce image distortion on the time scale of once each hour is very reasonable.

3.2.7. Coronal Velocity and Density in Active Region Loops

At 1 arcsec^2 spatial resolution with 1 second exposures using a spectrograph with only a 1% efficiency at the wavelength of the IR Fe XIII line at 1074.6nm the ATST is predicted to have a (one sigma) velocity sensitivity of about 37 meters per second (Penn et al 2002). Using the ratio of the two Fe XIII emission lines the density sensitivity is expected to be $1x10^5$ electrons cm^{-3}. Recent loop flow models by Winebarger et al (2002) predict loop electron densities of about 10^9 to several times 10^7 cm^{-3}, and plasma velocities on the order of 10s of km s^{-1}.

Based on scanning a single spectrograph slit across the nominal ATST FOV (180 arcsec) maps of the Doppler velocity and electron density in coronal active region loops can be made with unprecedented accuracy with a three-minute cadence. Such observations have the potential to reveal …. Such observations will constrain current models by providing….

What about time variability?

Penn et al, 2002, ATST Coronal Working Group Report, ATST Report #0001

Winebarger, A.R., Warren, H., van Ballegooijen, A., DeLuca, E.E., Golub, L.: 2002, Astrophys Jour, 567 L89.

Main Science Questions:

- What flow velocities exist in active region loops ? How does the velocity vary along the loop ?
- What is the density in active region loops as a function of distance along the loop ?

Observational Requirements:

Spectral coverage:

Fe XIII 1075nm, Fe XIII 1080nm, Si X 1431nm and other coronal emission lines will provide windows to seek variability in the coronal emission.

Field of view:

The entire FOV of the ATST must be accessible. The ATST limb height pointing requirements will depend upon the FOV used.

Spectral resolution:

A nominal dispersion of about 0.04nm per pixel for 5 pixels across the 1075nm (0.2nm width) coronal emission line is required.

Spectral coverage:

For proper background subtraction several continuum measurements must be made outside of the line emission. For the density measurements both 1075nm and 1080nm Fe XIII emission lines must be observed simultaneously.

Spatial resolution:

A one-arcsecond pixel is minimum requirement (match current and planned space-based coronal imagers). Goal: 0.”5

Off-limb pointing capability:

Ability to observe from 1.1 to 1.5 solar radii

Sky brightness:

A target value is 25 millionths of disk center brightness. The total background intensity target value is below 50 millionths. See Penn et al 2002, ATST report 0001.

Instrumental scattered light:

A target value is 23 millionths of disk center brightness from dust and mirror roughness. The total background intensity target value is below 50 millionths. See Penn et al 2002, ATST report 0001.

Time resolution:

An exposure time of the order of one second is desired to enable scanning a large FOV with temporal cadence on the order of a few minutes.

3.2.8. Coronal Intensity Fluctuation Spectrum

The required energy deposition rate to heat the corona is 1×10^7 erg cm$^{\{-2\}}$ s$^{\{-1\}}$ and Parker (1988) proposed that small magnetic reconnection events called nanoflares occurred with roughly 20% of this energy during a 20 second time period. What does this mean in terms of emission in the 1075nm [FeXIII] line? The temperature of this line (about 1.3MK) is suitable for observing some of these nanoflare events. Hudson (1991) proposed that the distribution of luminosity of a nanoflare in a particular spectral line would follow the same distribution of luminosity observed in larger flares, and he estimates that for Hα $L_{\_H\alpha}/L_{\_tot} = 0.05$. As H$\alpha$ represents cooler material, more emission is expected at [Fe~XIII] temperatures, but the [Fe~XIII] line is inherently weaker, and we assume these two effects cancel and use $L_{\_FeXIII}/L_{\_tot} = 0.05$. Dividing by 4π steradians we find that a nanoflare would release roughly $E_{\_nano}$ ~=~8×10^3 erg cm^{-2} s^{-1} sr$^{\{1}$ A^{-1}. As discussed in the ATST Coronal Working Group report (Penn et al 2002) the expected sensitivity (1 sigma) of the ATST is about 4×10^6 erg cm^{-2} s^{-1} sr^{-1} A^{-1}, or roughly $E_{\_nano}$ ~=~σ / 500 .

At 1 arcsec^2 spatial resolution with 1 second temporal resolution the 1074.6nm observations would be insensitive to nanoflares by several orders of magnitude. Recent work by Aschwanden & Parnell (2002) has used TRACE and Yohkoh observations to place constraints on nanoflares with much larger spatial pixels and with much slower cadence observations. Using the same 4 arcsec^2 spatial resolution and the 80 second temporal cadence, these proposed ATST observations gain a factor of 36 in signal to noise, and then the 1σ noise level becomes roughly σ ~=~15 $E_{\_nano}$. While Aschwanden \& Parnell expect major nanoflare activity at low heights in the corona (at heights of 1.03 R_{sun} events higher in the atmosphere (at heights of 1.3 to 1.5 R_{sun} are also expected where streamer and active region loop evolution are likely to produce magnetic reconnection events.

Aschwanden & Parnell, C.E. : 2002, Astrophys Jour 572 1048

Parker, E.N. : 1988, Astrophys Jour 330 474

Penn et al, 2002, ATST Coronal Working Group Report, ATST Rept #001

Hudson, H.S. : 1991, Solar Physics, 133 357

Main Science Questions:

- What is the calibrated peak flux in events versus the rate of events ?
- What is the size distribution of events ?
- What is the height distribution of events ?
- How are these events related to CME events ?

Observational Requirements:

Spectral coverage:

Fe XIII 1075nm, Fe XIII 1080nm, Si X 1431nm and other coronal emission lines will provide windows to seek variability in the coronal emission.

Field of view:

The entire FOV of the ATST must be accessible. The ATST limb height pointing requirements will depend upon the FOV used.

Spectral resolution:

Intensity measurements integrated over the entire coronal emission line (0.2nm width at 1000nm) are required with strictly simultaneous measurements in the nearby continuum. There must be at least two continuum channels to measure the background to attain the signal to noise levels discussed here, see Penn et al 2002.

Spatial resolution:

A one-arcsecond pixel is desired, although to achieve the required signal to noise ratio several pixels may be summed together. The spatial structure of these events is largely unknown.

Off-limb pointing capability:

Ability to observe from 1.1 to 1.5 solar radii

Sky brightness:

A target value is 25 millionths of disk center brightness. The total background intensity target value is below 50 millionths. See Penn et al 2002, ATST report 0001

Instrumental scattered light:

A target value is 23 millionths of disk center brightness from dust and mirror roughness. The total background intensity target value is below 50 millionths. See Penn et al 2002, ATST report 0001

Time resolution:

An exposure time of the order of one second is desired, although to achieve the required signal to noise ratio the exposures may be averaged during a one-minute time period.

3.3. ACTIVE REGION EVOLUTION

3.3.1. Dynamo processes in deep layers of the convection zone

Science questions:

- How twist/helicity evolves during flux emergence, when a flux tube crosses photosphere-chromosphere boundary.
- How twist/helicity evolves after emergence.
- Pattern of twist/helicity during flux emergence
- How twisted/current-carrying flux tubes interact with each other during evolution of active region (flux tubes coalescence?)
- What are asymmetries (between leading and following polarities) in magnetic flux, inclination, Doppler velocities during flux emergence.
- What are conditions in the photosphere and chromosphere prior new flux emergence (vertical/horizontal flows, magnetic field topology/distribution)
- What is 3-D topology and helicity (electric currents) of emerging field, do they show a presence of kinked loops?
- Is there a reconnection between emerging and pre-existing fields?
- How twist/helicity evolves during active region dissipation.

Observational requirements:

Spatial resolution:

Minimum of 70 km, to resolve individual flux tubes. Goal: 35 km

Trade-offs between resolution and polarimetric sensitivity will be necessary.

Vector magnetic field:

Field-Strength:	+/-100G
Inclination:	+/- 5 deg.
Azimuth:	+/- 10 deg.

Velocity:

Doppler shift: +/- 25 m/s

Horizontal shift: +/- 50 m/s

Time resolution:

during flux emergence - < 20 sec

after emergence - few minutes?

Field-of-view:

emerging flux: 50-100 arc sec.

later stages of emergence, mature region - 3 arc min (minimum), 5 arc min (goal)

Spectral coverage:

Simultaneous visible, near IR(1.56micron) and/or 12 micron lines

Spectral resolution:

1 pm (visible)

Polarimetric sensitivity:

10^{-4} Ic (visible), 10^{-3} (NIR)

3.3.2. Solar flares

Science Questions:

- With observations of un-paralleled resolution from ATST, we should be able to make significant progress in solar flare studies in the following two areas:

(1) Fine temporal and spatial structure of flares

The explanation of the sub-second structures in terms of hard X-ray time profiles, will directly point to the critical issues about the nature of flare energy release, and the properties of the source of particle acceleration. The nature of these sub-second peaks is not yet clear, but one hypothesis is that **magnetic reconnection occurs almost continuously among small flux tubes**, and non-thermal electrons are, thereby, constantly injected into the chromosphere on a **sub-second time scale.**

(2) Structure and evolution of magnetic fields in flaring active regions

- What is the role of the evolution of the photospheric and chromospheric magnetic field in triggering solar flares
- What is the relationship between the magnetic configuration and the properties of flares?
- How do electric currents evolve in time and height, and what is their relationship to particle precipitation?

- What are the positions of the microwave and hard X-ray flare footpoints relative to the structure of the magnetic fields?

- What are the eruption and acceleration mechanisms?

- What is the process of building magnetic shear in active regions?

- Relationship between the structure of magnetic fields and solar flares?

- How does magnetic shear change immediately before and after major flares?

- What role does photospheric magnetic shear play for flares?

- Very small changes of magnetic fields associated with flares require a high polarization sensitivity and accuracy. Such a requirement is also driven by the accuracy for the photospheric boundary condition to carry out 3-D force free extrapolation to understand the 3-D magnetic structure associated with flares.

Observational Requirements:

Spatial resolution:

0.” 05 in the visible; 0.”1 in the near IR

These observations will provide details of flare energy precipitation on fine temporal and spatial scales.

Temporal Resolution:

As fast as 10 ms: High cadence X-ray and microwave observations have demonstrated temporal fine structure (sub-second) in solar flares, called elementary flare bursts. They may be attributed to the fine structure in the coronal magnetic fields, related to the aggregation of photospheric magnetic fields into ``magnetic knots". ATST shall provide high cadence (10 ms) and high spatial resolution (<0.1") observations, which will provide the observational evidence to verify this picture.

Field-of-view: 3 arcmin; goal (5 arcmin)

Wavelength coverage:

Simultaneous visible, near IR , thermal IR. By combining high cadence optical imaging (H-alpha, D3) with hard X-ray imaging from missions (such as HESSI), as well as with high resolution magnetograms (FeI 630.25 nm, 1.083 micron, 1.56 micron, 12 micron), we expect to learn if and how, the individual sub-second peaks in the hard X-ray and microwave time profiles correspond with the rapid precipitation along various flux loops. as D3 and off-band Hα.

Spectral resolution: 1- 2 pm (visible)

Magnetic Field Vector:

Accuracy of magnetic field to be 1 $\mathrm{Mx/cm^2}$ in the line of sight component with a sensitivity of 0.1 $\mathrm{Mx/cm^2}$, and 25 $\mathrm{Mx/cm^2}$ in transverse component with a sensitivity of 10 $\mathrm{Mx/cm^2}$.

Field strength: +/- 100G

azimuth: +/- 1 degree

inclination: +/-1 degree

Polarization accuracy and sensitivity:

Using the FeI 630.25 nm spectral line as an example, the above requirements for the magnetic field vector determination translate into the following polarization sensitivity requirements:

sensitivity: $7 \cdot 10^{-5}$ in Stokes V, Q and U

accuracy: $5 \cdot 10^{-4}$.

Operational:

ATST observations have to be coordinated with observation from space instruments such as HESSI, SDO.

4. TOP LEVEL TELESCOPE REQUIREMENTS

The science goals listed in Section 3 lead to the following top-level requirements on the telescope.

4.1. RESOLUTION

The ATST shall have a minimum aperture of 4 meters. ATST shall have a high order adaptive optics (AO) system. The AO system shall provide diffraction-limited spatial resolution (λ/D=0.026 arcsec at 500 nm, λ/D=0.033 arcsec at 630nm, λ/D=0.083 arcsec at 1.6 μm) within the isoplanatic patch (of order 5-10 arcsec in the visible) and with a Strehl ratio of S(630nm) > 0.6 (goal S>0.7) during excellent seeing conditions (r0(630nm) > 20 cm). During good seeing (r0(500nm) > 7 cm) Strehl ratios of S(500nm)> 0.3 will be achieved. The AO system shall improve the image quality to sub-arcsecond resolution over a larger field of view (arcminutes) by correcting the near-ground seeing that often dominates the day-time seeing. These partially corrected data will be further processed using post-facto image processing techniques such as phase diversity to arrive at diffraction-limited observations.

Source: SRD, sections 1-3

For seeing limited observations (no AO) and during the best seeing conditions at the site the telescope shall not be a performance limiting factor.

Source: SRD, section 3

4.2. PHOTON FLUX AND SENSITIVITY

The science goals require an instrument that enables high-resolution observations in the most general sense. High resolution includes high-spatial, high-temporal, and high-spectral resolution. Achieving high spatial, temporal and spectral resolution simultaneously requires a minimum collection area of at least 4m and the highest possible throughput of telescope and instrument(s). The requirement for high photon flux is an equally strong driver toward large aperture as is angular resolution. **The ATST shall provide a minimum collecting area of 12 m^2.**

Note: The number of photons per angstrom per second per diffraction-limited angular resolution element is independent of aperture size. Therefore the telescope will not always be operated at the diffraction limited. Each observational procedure will be the result of an optimization process, which optimizes spatial, spectral and temporal resolution and signal-to-noise ratio.

Source: SRD, sections 1-3, CLEAR R&D note 97-7

4.3. POLARIZATION SENSITIVITY AND ACCURACY

Polarimetric measurements shall in most cases be limited in sensitivity and accuracy by the photon noise. However, certain observations will be limited by systematic errors due to the influence of the telescope on the polarimetric measurements. ATST shall achieve a polarization sensitivity of 10^{-5} and a polarization accuracy of $5 \cdot 10^{-4}$.

Source: SRD, sections 1-3, see also : Sol. Phys. 155, 1 ; ApJ, 110, 357

4.4. SCATTERED LIGHT

A low scattered light facility is a requirement for the coronal capabilities of the ATST but also for many disk observations.

Photosphere:

Large sunspots with field strength in excess of 3 kG often have residual intensities of less than 10%. In order to accurately measure physical parameters in the umbra, the umbral signal must be at least an order of magnitude above the scattered light from the surrounding photosphere.

The scattered light from telescope and instrumentation from angles > 10 arcsec shall be 1% or less (see section 3.1.7).

Source: SRD, sections 1-3

Chromosphere (near –limb observations):

For Hanle measurements the scattered light shall be less than 10^{-4} of disk intensity at heights 5-50 arcsec above the limb (see section 3.1.6). The structures near the limb have an intensity of about 10^{-3} of the disk center intensity for the integrated line emission (1083nm). This means the stray light requirements are well reduced from the coronal requirements.

Source: SRD, sections 1-3

Corona:

The sky scattered light at the ATST site must be better than 25 millionths for much of the time (see site requirements, section 0) and the total instrumental scattered light (dust plus mirror roughness) shall be 25 millionths or less at 1000nm and at 1.1 radii. Values larger than these levels require longer integration times to achieve the desired signal to noise levels. See 3.2.5 and Coronal Working Group report.

Source: SRD, sections 1-3

4.5. FIELD OF VIEW (FOV)

- This heat stop at prime focus shall pass an unvignetted 5-arcmin circular FOV.
- The Nasmyth Station shall receive a 5-arcmin circular FOV
- The minimum FOV at Coudé Station shall be a 2-arcmin square FOV (2.83 arcmin circular). With this FOV the ATST shall achieve the Strehl requirements specified in sections 4.1, 5.1.1.
- The full 5-arcmin circular FOV shall be available at Coudé Station at a possible reduced Strehl due to non-optimal thermal control of optical elements such as the deformable mirror. This option is intended for infrared observations ($\lambda > 1.6$ micron).
- These requirements lead to the following **derived requirement**: There must be a facility for a changeable field stop at the Gregorian Focus.

In order to allow studies of the evolution of entire active regions, prominences and coronal structures, the ATST shall provide a minimum field of view (FOV) of 3 arcmin. The goal is to achieve a FOV of 5 arcmin. As a future upgrade option we might consider implementing a FOV of 1 solar radii for coronal observations, which will require a changeable heat stop and likely a larger secondary.

Source: SRD, sections 1-3

4.6. WAVELENGTH COVERAGE

In order to address the scientific problems stated above, a wide range of diagnostic tools has to be applied. The ATST shall be a well-instrumented telescope that allows combination of different instruments covering a large wavelength range from the UV to the thermal infrared. The ATST shall cover the wavelength range from 0.30 – 28 μm.

Source: SRD, sections 1-3

4.7. FLEXIBILITY

- Simultaneous multi-wavelength observations at visible and IR wavelength must be possible.
- Simultaneous observations with different instruments must be possible.
- In addition to facility type instruments an observing room environment with optical benches for user instrument setups must be provided. The solar image fed to the observing room has to be de-rotated. De-rotation without additional optics, e.g., a rotating Coude platform, is preferred.
- Maximum scientific productivity requires easy and fast (< 30min) switch between various facility instruments.

Example: the observer must be able to combine spectrograph and imaging devices as well as polarimeters operating at different wavelength (e.g., visible, NIR). In order to achieve the flexibility goal instrumentation will be designed using a modular approach, which allows use of the same modules to “assemble” different instruments. For example, the same polarimetry package can be used in combination with a spectrograph or a narrow-band imaging filter system.

Source: SRD, sections 1-3

4.8. LIFETIME

The ATST is expected to be the major solar ground based facility for a minimum of two (2) decades. The useful lifetime of ATST is expected to exceed 40 years.

Source: SRD, sections 1-3

4.9. ADAPTABILITY

The ATST will serve a large number of users from the national and international community. The scientific focus and in turn instrumentation and observing tools used at the telescope are likely to change significantly during ATST’s lifetime as has been the case for the current solar National facilities (e.g. DST, McMath-Pierce). The ATST shall be designed with a minimum of limitations for future use and in a way that allows future upgrades and the addition of new instruments.

Source: SRD, sections 1-3

4.10. AVAILABILITY

This defines the percentage of the time the telescope will be available for observations during normal clear time and time not scheduled for scheduled engineering/maintenance (10-15%). This is often also referred to as reliability. Some night-time observatories have achieved 97-98% availability.

Source: SRD, sections 1-3

4.11. LOCATION

The best affordable site in terms of seeing, sky clarity and sunshine hours shall be chosen in order to maximize the telescope performance and minimize the cost of adaptive optics (see section 5.1.1 and 5.9.)

Source: SRD, sections 1-3

4.12. NIGHTTIME OPERATIONS GOALS

While the first priority for the ATST---scientifically, technically, and operationally---is advanced observations of the Sun, the possibility will exist for the application of the ATST to non-solar observations that can address astrophysical problems in a novel manner. In this regard, the ATST can potentially complement other astronomical facilities in selected and restricted areas of contemporary astrophysics.

In particular, the ATST may be unique among all solar or night-time telescopes by providing a 4-m aperture, true coronagraph with an unobstructed pupil. As in the case of other solar telescopes, which have been used for non-solar observations, such as the NSO McMath-Pierce Solar Telescope on Kitt Peak, ATST will have the ability to point at targets very near the Sun. Moreover, the projected first generation instruments for ATST will enable programs involving high spectral resolution spectroscopy and spectro-polarimetry to be conducted. From an operational perspective, the ATST will present an opportunity for large time-block scheduling of synoptic observations requiring a long temporal baseline of observations.

5. DETAILED/DERIVED REQUIREMENTS

5.1. IMAGE QUALITY SPECIFICATIONS

The ATST's highest priority science goal is to achieve diffraction limited spatial resolution (with the full 4m aperture) observations of the solar atmosphere. The adaptive optics (AO) system is crucial in achieving this goal and ultimately the performance of the adaptive optics system will be the limiting factor for the image quality. However, there are cases where the observer might choose to perform observations without AO. Examples are observations requiring the highest possible throughput, simple instrument setups that can be installed easily and quickly in, e.g., a queue observing scenario, coronal observations for which at least initially no AO system will be available. Both, AO and non-AO observations will be considered in defining the image quality requirements. We note that the AO observations are considered to be the most important ones.

Image quality requirements vary for different scientific programs. For high resolution imaging programs, which utilize post-facto PSF estimation (e.g. phase diversity) and image reconstruction a low Strehl ratio might be sufficient. Although it is obvious that high Strehl ratios will improve the S/N in these observations.

For spectroscopic and, in particular, polarimetric observations maximizing the energy concentrated in the diffraction limited core of the PSF, i.e., maximizing the Strehl ratio is crucial. For observations of point sources (night time) energy spread from the diffraction limited core into the seeing halo, i.e., outside the spectrograph slit results in increased exposure times, i.e., loss of observing efficiency. For extended objects such as the sun the situation is much more complex. The seeing halo (width of order 1") causes light from, e.g., granules and intergranular lanes, or Stokes spectra from adjacent features, e.g., different polarities, to be mixed together. The problem becomes more severe as the Strehl ratio becomes smaller. The interpretation of these data may become difficult to impossible.

Post facto image reconstruction is therefore an important tool that will greatly aide in the correct interpretation of such data. For example, accurate photometry will in most cases require some kind of post facto image processing. Post-facto image reconstruction techniques that use the information about the corrected wavefront available from the adaptive optics wavefront sensor are currently under development and can expected to be available on a routine basis long before ATST first light.

For coronal observations but also for many disk observations minimizing the intensity in the far wings of the PSF is essential.

Assumptions and considerations:

1) The ATST site has not been selected as of Dec. 2001 and therefore the seeing statistics at the ATST site are not known at this point. We will use the seeing distribution measured at Sac Peak by Brandt et al 1987 as a baseline. The median seeing at SP is 9cm. However, in solar astronomy new and ground-breaking observational results often are achieved during the best seeing conditions. Therefore image quality requirements shall not be derived based on median seeing but based on the best seeing available at the site. At SP r_0 > 18cm is achieved during 10% and r_0 > 25cm are achieved during 5% of the time. The LEST site survey results indicate that better sites may exist. We use r_0 =25 cm as a best seeing case.

2) The telescope's optical performance shall be optimal during the best seeing conditions. The seeing at known sites is typically at its best in the morning hours (lake sites may be different). The system performance may degrade proportionally as the seeing degrades over the course of the day. This allows to us tailor the requirements to the best conditions and trade aspects that

might be time of day dependent. E.g., the thermal control design could be optimized to emphasize the best seeing time, allowing a trade in thermal control performance later in the day (when we might want to start the process of getting the telescope thermal aspects set for the next morning).

3) Image quality will be specified in form of diameter for 50% and 85% encircled energy. (The PSF of a perfect telescope concentrates roughly 50% of the energy is within λ/D (the diffraction limit) and 85% of the energy within a diameter of 2.44 λ/D). The image quality specifications include all internal (self induced) seeing sources, such as mirror and dome seeing, seeing generated by the telescope structure and seeing along the light pass to the instrument focal plane(s). Unless specified otherwise the image is assumed to be tip/tilt corrected (e.g., short exposures of order < 10 ms or fast tip/tilt corrected long exposure). The image quality requirements are derived for seeing limited observations and for observations limited by adaptive optics performance.

4) Note**:** During these excellent seeing conditions AO will perform the best and deliver the highest possible image quality, i.e., for observation programs, which require high resolution Adaptive Optics SHOULD BE USED!

5) The image quality requirements are specified at different wavelength and refer to the instrument focal planes (including coudé observing room). The specified image quality requirements will be achieved over a minimum FOV of 3 arcmin. Goal: 5 arcmin.

5.1.1. Diffraction limited observations with adaptive optics:

Specification:

The ATST shall provide diffraction-limited observations (at the detector plane) with high Strehl (S>0.6 required, S>0.7 goal) at 630 nm and above during excellent seeing conditions (r_0 (630 nm) > 20 cm) and S > 0.3 at 500 nm and above during good seeing (r_0 (500 nm) = 7 cm).

Source: SRD, sections 3-4

High Strehl ratios, i.e., a high order AO correction, is a derived requirement that results from many of the science requirements discussed in sections 2 and 3. For example, polarimetric studies of mixed polarity fields, which may occur on scales of 30 km require diffraction limited resolution with high Strehl. The requirement to concentrate 99% of the polarimetric signal within a 0.”3 diameter (section 3.1.3) is another strong driver for high Strehl ratios as can be inferred from Fig. 1. Figure 1 plots the Strehl ratio required to concentrate 99%, 90% and 80% of the energy with 0.”3 and as a function of the Fried parameter r_0. It is obvious that good seeing conditions make it much easier to achieve this goal since in good seeing conditions:

1) Less DoFs are required to achieve high order of correction
2) The wavefront sensor S/N is high, i.e., high order correction can be achieved
3) The width of the seeing halo is smaller, i.e., the 99%EE in 0.”3 is achieved with lower Strehl ratios

This calculation ignores the fact that adaptive optics will also decrease the width of the seeing halo (results in lower Strehl ratios) and it is assumed that no post facto image processing was applied.

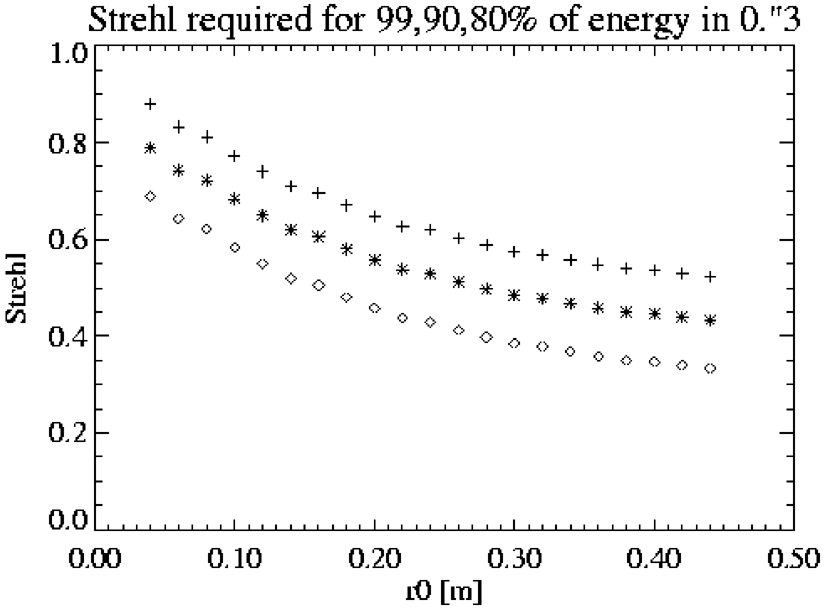


Fig 1. Strehl required to meet the 99%, 90% and 80% EE within 0.”3 requirement.

The 99% within 0.”3 requirement is based on experience. A detailed simulation using model AO-corrected PSFs to convolve the output of MHD simulations such as provided by R. Stein. The variation in time of the PSF will be taken into account to predict the accuracy of polarimetric measurements as a function of AO performance (strehl). Figures 2a/b demonstrate the effects of a partially AO corrected PSF for different levels of correction (Strehls) in a very qualitative way. For comparison the uncorrected long exposure is shown also.

Figs. 3 and 4 show initial results from the numerical simulation using the Nordlund and Stein MHD model and radiative transfer calculations for the FeI line 633.2 nm. Shown are intensity and corresponding Stokes-V signals in an 8”x8” FOV. The data were convolved with (partially) AO corrected PSFs. In this particular example the Strehl ratio varies from S=0.001 (seeing limited) to S=0.55. The images convolved with the aberration-free telescope PSF as well as the original images are also shown. Fig. 4 compares simulated “observed” quantities to the input values. For Stokes-V a (nearly) linear relationship is maintained only for Strehl ratios S > 0.4-0.5. Also the fraction of the detected flux is directly given by the Strehl ratio, i.e., for a Strehl of S=0.5 50% of the flux present in these MHD simulations would be detected by the observations (Keller). These initial simulations clearly demonstrate the need for high Strehl ratios to be provided by the ATST AO system. It is unlikely that such high Strehl ratios can be provided for visible wavelengths in median seeing conditions. The “high Strehl science” will be performed in good-excellent seeing conditions (r_0 > 15cm). Making use of new technology developments the ATST AO shall strive to provide the highest order correction possible.

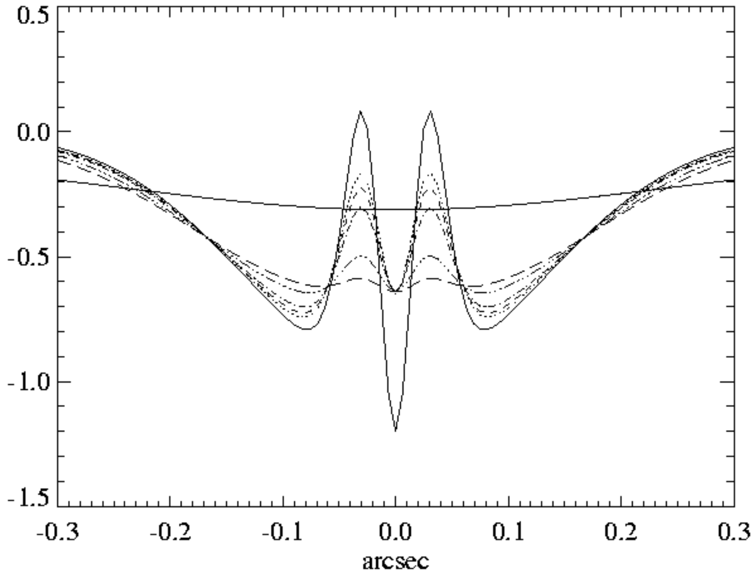


Fig.2a: Simple (qualitative) model of flux tube with hot walls located in intergranular lane convolved with AO corrected PSF assuming different degrees of correction. Solid line: model; Dotted: perfect 4m telescope. Dashed: S=0.85; Perfect zonal AO correction with d/r0=1. Dash-dotted: S=0.7, Dash-dotted: S=0.3, Long-Dash: S=0.1, Solid: uncorrected long exposure.

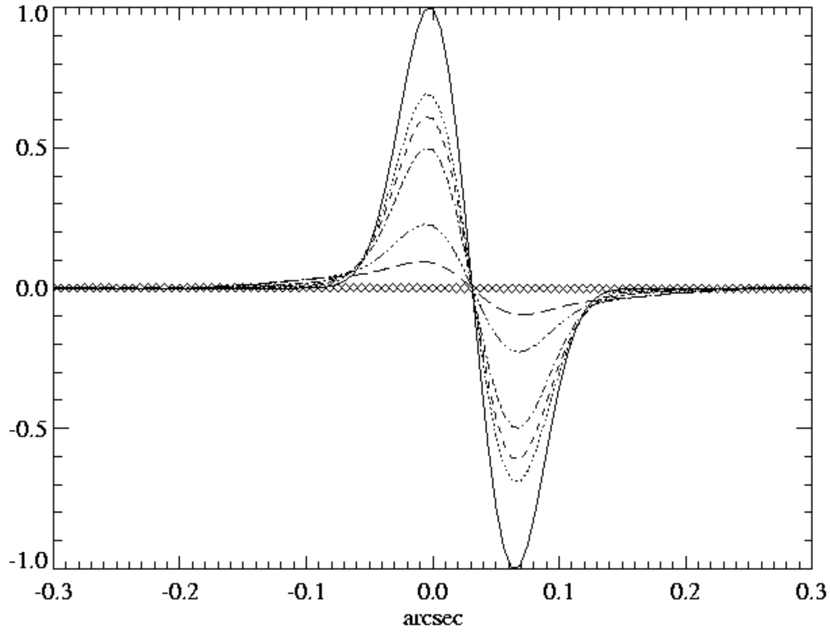


Fig.2b: Simple (qualitative) model of mixed polarities of size ~0.”05 separated by ~0.”05. The effects of the PSF assuming different degrees of correction are shown. Solid line: model, polarization signal normalized to max; Dotted: perfect 4m telescope. Dashed: S=0.85; Perfect zonal AO correction with d/r0=1. Dash-dotted: S=0.7, Dash-dotted: S=0.3, Dashed: S=0.1, Diamonds: uncorrected long exposure.

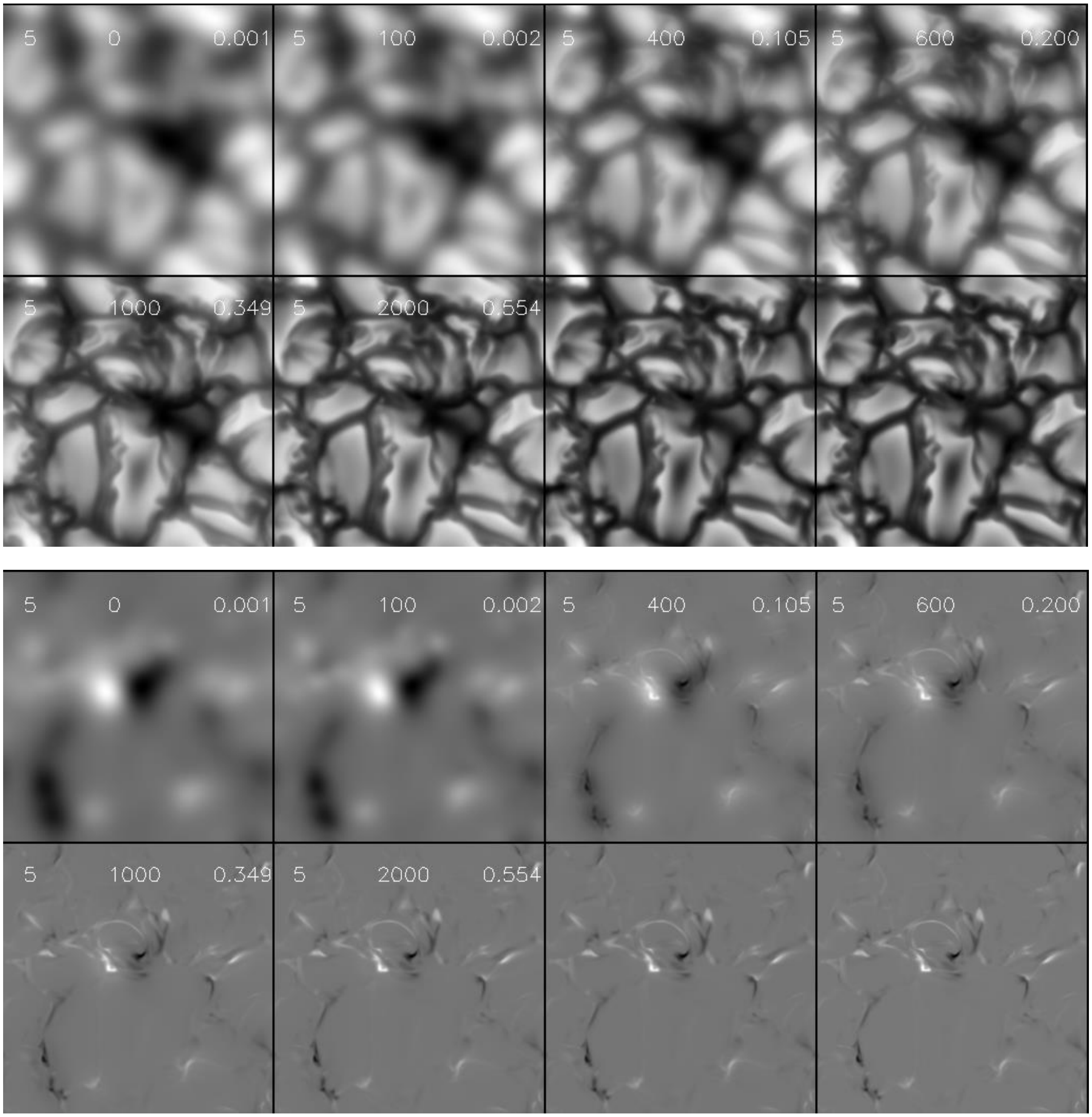


Fig. 3: Nordlund & Stein MHD simulation of granulation convolved with long exposure PSF of ATST for various degrees of correction. Upper panel: intensity. Lower panel: Stokes-V. Parameters are: r0 = 5cm; number of corrected modes (0-2000); achieved Strehl (courtesy B. Stein). The two images on the lower right are image convolved with ideal telescope PSF and the original image.

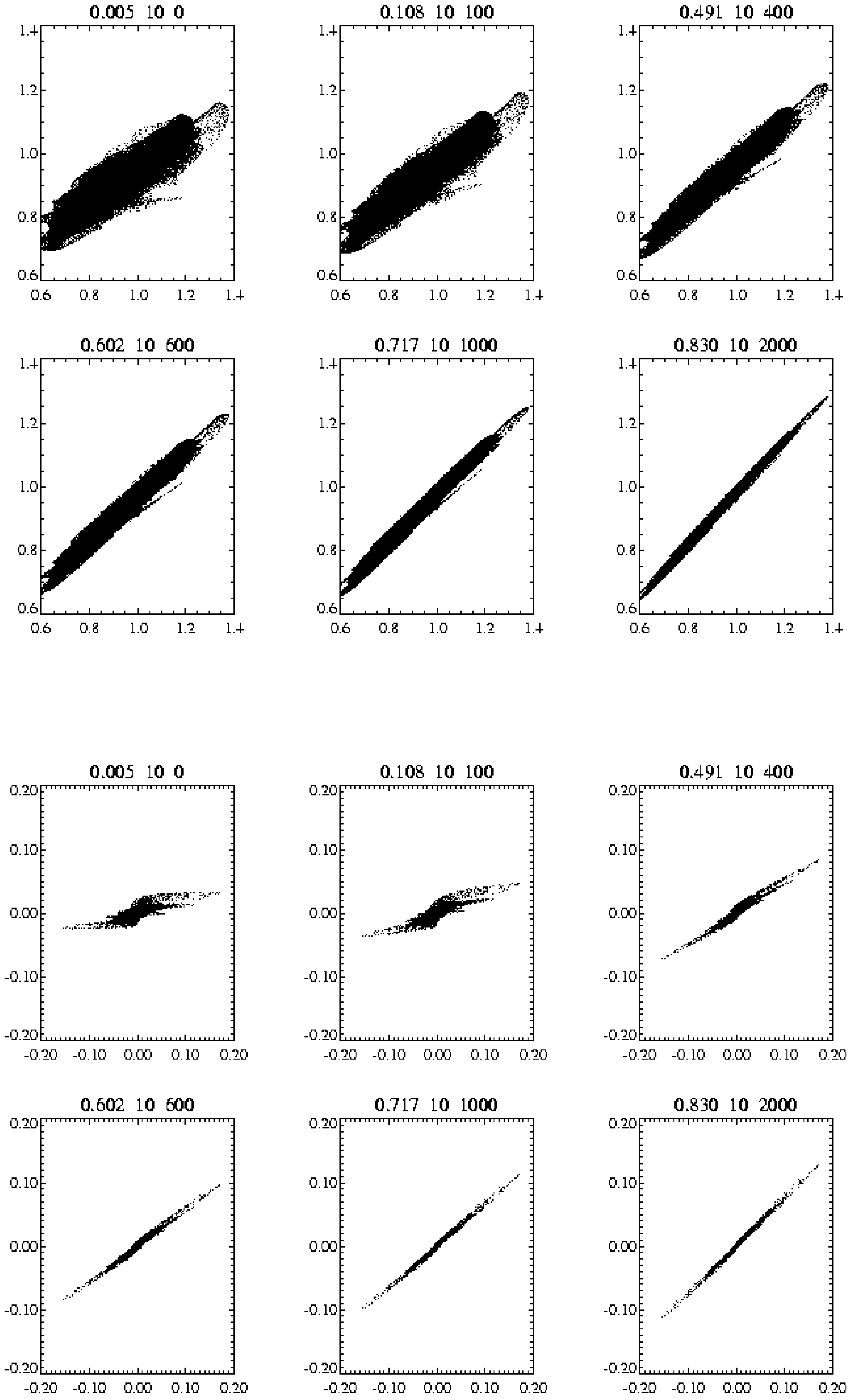


Fig. 4: “Observed” intensity and Stokes-V signals vs. input signals as a function of Strehl delivered by the AO system.

5.1.2. Seeing limited observations

Specifications:

Disk Pointing:

- At optical wavelength and without AO, ATST will be truly seeing limited. The telescope shall not degrade the best seeing profile (5 percentile) by more than 10%.
- At NIR and IR wavelength and tip/tilt control near diffraction limited resolution with reasonably high Strehl ratio can be achieved. The telescope shall not significantly degrade the diffraction-limited PSF. A minimum requirement for the delivered image quality: FWHM of the delivered PSF shall be < 0”.15 at 1.6 micron for on disk observations (closed loop active optics).

Off-Limb Pointing:

- Corona: Assumes open-loop active optics. At NIR wavelengths (1 micron) the ATST shall deliver an image quality of < 0.”4 FWHM. A goal is to deliver a PSF with FWHM < 0.”2.
- **Goal**: Near-limb (Spicules, prominences): Assumes open-loop active optics. At visible wavelengths (e.g. 656.3 nm) the ATST shall deliver a PSF with FWHM < 0.”1 (see section 3.2.4).

  Note : This requirement is based on the assumption that wavefront sensing for active optics optics and tip/tilt control can be done on prominence structure(Hα). A future laser guide star upgrade that would enable coronal AO observations would provide a solution to achieving this goal.

Source: SRD, section 3

Examples:

5.1.2.1. Seeing limited on-disk observations:

Solar astronomers have long utilized short exposure imaging to achieve high resolution. This is applicable to relatively broadband imaging and aided by the small aperture size of existing solar telescopes since the amount of tilt removed in short exposure images (or stabilized long exposures) depends on the telescope aperture. For small apertures diffraction limited short exposure images can be achieved during excellent seeing. At large aperture telescopes and at visible wavelength, however, the probability for achieving diffraction limited imaging without adaptive optics is extremely low since even for the highest r_0’s expected the residual wavefront variance of the higher order modes leads to very low Strehl ratios (Case 1).

Case 1:

D=4m, visible wavelength: 500nm, best seeing conditions: $r_0(500\text{nm}) >= 25$ cm; The residual wavefront variance after tip/tilt correction is:

$$\sigma^2 = 0.134\ (D/r_0)^{5/3} = 13.6\ \text{rad}^2 \text{ or a Strehl of } S = 1.2\text{x}10^{-6}$$

(In comparison, for a 50cm telescope and r_0=25 cm: σ^2 =0.42 rad²; S=0.65).

Note: Post facto image reconstruction techniques (e.g., Phase Diversity) commonly utilized to achieve diffraction limited imaging from small aperture solar telescopes will suffer from S/N problems when applied to the 4m ATST. At least a low order AO correction will be required for such techniques to produce good results.

At 500 nm and r_0=25cm, the FWHM of the seeing limited PSF is 0.”4. The telescope shall not add more than 10% to the FWHM of the seeing limited PSF resulting in a delivered PSF with FWHM <=0.”45.

50% Encircled Energy Diameter < 0.”2

85% Encircled Energy Diameter < 0.”5

Case 2:

D=4m, NIR wavelength: 1.6 micron, excellent seeing conditions: r_0(1.6 micron) >= 100cm ; 5 percentile of Sac Peak r_0 distribution). The residual wavefront variance after tip/tilt correction is :

$$\sigma^2 = 0.134\ (D/r_0)^{5/3} = 1.25\ \text{rad}^2 \text{ or a Strehl of } S = 0.26$$

I.e., during excellent seeing useful Strehl ratios can be achieved with simple tip tilt correction and the use of post facto image reconstruction utilizing short exposures will be possible at NIR wavelength.

Minimum requirement: **50% Encircled Energy Diameter < 0.”15**

Goal: At NIR wavelength a degradation of the **diffraction limited PSF** (FWHM=0.”083 at 1.6 micron) of 20% (or less) is desirable.

50% Encircled Energy Diameter < 0.”1

85% Encircled Energy Diameter < 0.”25

Note: Maintaining the width of the central core (i.e., the 50% EE requirement) is the more important requirement.

Case 3:

D=4m, IR wavelength: 4 micron, excellent seeing conditions: r_0(4 micron) >= 300cm) The residual wavefront variance after tip/tilt correction is :

$$\sigma^2 = 0.134\ (D/r_0)^{5/3} = 0.22\ \text{rad}^2 \text{ or a Strehl of } S = 0.8$$

At IR wavelength a degradation of the diffraction limited PSF (FWHM=0.”25 at 4.8 micron) of 20% (or less) is acceptable. Required image quality:

50% Encircled Energy Diameter < 0.”3

85% Encircled Energy Diameter < 0.”7

5.1.2.2. Seeing limited observations of the corona.

Unless correlation tracking can be done on coronal features (e.g., Hα prominences, appears feasible but not demonstrated yet) it has to be assumed at this point that no tip/tilt correction will be applied and active optics will operate in open loop mode.

Case 1: Coronal Magnetometry

Off-pointing up to 1.5 solar radii; wavelength: 1 micron, excellent seeing conditions: r_0(1 micron) >= 50 cm, FWHM seeing limited PSF 0.”4.

The minimum resolution required for coronal magnetometry is 2 arcsec. A resolution of 0”.5 is desired.

The Telescope shall deliver the following image quality:

50% Encircled Energy Diameter < .7 **Goal: 50%EE within < 0.”4**

85% Encircled Energy Diameter < 2” **Goal: 85% EE within < 1”**

Scattered light in the far wings of the PSF will be controlled to < 25e-6 of I_disk at 1.1 solar radii.

The integration time for high S/N coronal observations of typically 1 hour determines the period of time over which the image quality has to be maintained.

Source: SRD 3.2.5

Case 2:

This science case Coronal Plasmoid Search (3.2.6) potentially pushes the image quality in the corona harder than the magnetic case.

Minimum requirement: 50% EE within 0.”4

Goal: 50% EE within 0.”2

Source: SRD section*: 3.2.6*

5.2. THROUGHPUT REQUIREMENTS

Gregorian Focus: **> 85% at all wavelengths.**

Note: assumes 2 reflections at > 92% (aluminum coatings)

Coude Observing Room: **> 60% at all wavelengths.**

Note: assumes 6 reflections at > 92% (aluminum coatings). Other, more efficient coatings (e.g. silver) may be considered. However, trade-offs of various science goals will be necessary, e.g., broadband throughput vs. transmission in UV.

Goal: **Maximum possible throughput.**

Source: SRD sections 1-4, CLEAR R&D note 97-7

5.3. FIELD OF VIEW

The heat stop at prime focus shall limit the usable FOV to 5 arcmin. The FOV may have to be limited further in secondary or tertiary image planes if required (driven by instrumentation). See section 4.5.

Source: SRD sections 3-4

5.4. SCATTERED LIGHT REQUIREMENTS

The top level requirements stated in section 4.4 have several implications for the ATST design: Because of the stringent scattered light requirements all of the photospheric (disk) light has to be rejected by an occulting system at prime focus. The heat stop shall serve as an (inverse) occulter for observations far enough (> 10") off the limb (maximum off-pointing 1.5 solar radii, see section "Pointing and Tracking").

Observations close (a few arcsec) to the limb are the most challenging. In addition to the inverse occulter a normal occulter (shaped to match solar limb at maximum solar radius) is required. This normal occulter has to be movable within the 5 arcmin FOV, rotatable, and capable to fast track limb motion due to seeing and telescope shake. The tracking signal may have to be derived from the prime focus image. Both heat stop and normal occulting disk shall be close to prime focus.

5.5. POLARIMETRY REQUIREMENTS:

In order to achieve the polarimetry requirements stated in section 4.3 (Polarimetric sensitivity: <$\mathbf{10^{-5}}$ Polarimetric accuracy : **$\mathbf{5x10^{-4}}$)** instrumentally induced polarization (Stokes I to Stokes Q, U, V) shall be 1% or less. Cross-talk (between Stokes Q, U and V) shall be limited to < 5%. Even at these levels any instrumentally induced polarization and cross-talk must be accurately calibrated. Depending on the telescope (and instrument) configuration, these calibrations have to be performed as a function of telescope pointing. In any case, these calibrations shall be performed at regular intervals since the instrumental polarization changes with the change in coating over time (e.g. growth of aluminum oxide layer on aluminum coatings).

Instrumental Polarization Calibration: must be known to an accuracy of at least $5x10^{-4}$

Instrumental Polarization Stability: Shall not change by more than $5x10^{-4}$ over 15 min.

5.6. POINTING AND TRACKING

Absolute (blind) pointing shall be accurate to <5 arcsec. Offset pointing shall be accurate to better than 0."5. Long exposures (~1h) are required for coronal observations. This requires a tracking stability of < 0."5 over > 1h.

Off-Pointing: Driven by Coronal requirements (section 3.2.5). Maximum off-pointing: 1.5 solar radii in all directions.

Sky coverage: Pointing within 10 degrees of horizon.

5.7. ACTIVE OPTICS

It is assumed that ATST will need an active optics system in order to achieve the image quality requirements.

For disk observations the active optics system shall operate in closed loop mode. The active optics wavefront sensor shall be able to track on granulation and other solar structure. The most likely wavefront sensor is a correlating Shack Hartmann type. A reference image is required to perform the cross correlations between reference and all other subapertures. Granulation evolves on time scales of minutes and typically the reference image has to be updated on this time scale. However, the active optics system is not required to measure or correct tip and tilt. This means that the reference can be updated continuously, i.e., a new reference is taken for each wavefront sensor image. The time available to perform an accurate measurement of the telescope wavefront (by averaging over many seeing realizations) is therefore determined by the timescale on which changes of the wavefront occur.

For coronal observations it is currently assumed that active optics will be operated in open loop mode.

The system shall be designed in a way that ensures graceful degradation in performance when seeing conditions degrade to a point that might not allow closed loop active correction.

5.8. TIP/TILT CONTROL

ATST shall have a fast tip/tilt correction system capable of correcting atmospheric and instrumental image motion to a level that is consistent with the specified image quality requirements

Bandwidth: Sufficient to control image motion to specifications during wind velocities that occur during median or better seeing conditions at the site (typically < 12 m/s). This specification will heavily depend on the site characteristics. For example, at the La Palma site good seeing conditions and strong winds often coincide where at the Sac Peak site high winds are usually detrimental to the seeing.

Preferred location for tip/tilt correction is the secondary mirror. The tip/tilt correction signal shall be derived from solar granulation and other structure such as pores and sunspots. The system shall be designed in a way that ensures graceful degradation in performance when seeing conditions degrade to a point that might not allow closed loop fast tracking.

For 4m aperture and worst case seeing scenario r_0= 2cm we require a tip/tilt correction range of 1.2 arcsec rms, or >3 arcsec P-V. However, the required tip/tilt range is likely to be determined by (wind induced) telescope shake. The requirements for the tip/tilt control system are therefore closely connected to the enclosure performance requirements (section 5.11).

5.9. ADAPTIVE OPTICS

Conventional Adaptive Optics: Initially ATST shall have a conventional (single conjugate, most likely to pupil plane) adaptive optics system that provides a high order of correction at visible wavelength. Within the isoplanatic patch the adaptive optics system shall achieve Strehl ratios of > 0.3 during good seeing conditions (r_0(500) > 7cm) for wavelengths > 500nm and S>~0.6 (goal 0.7) during excellent seeing conditions (r_0(630nm) > 20cm) for wavelengths > 630nm (see 5.1.1).

(Note: The isoplanatic angle is defined as the angle at which the Strehl has dropped by a factor 1/e and is of order a few arcsec.)

Time sequences of consistent image quality are required for achieving many of the science goals. Spectral or spatial scans often suffer from varying image quality during the scan. The AO system shall provide consistent image quality during varying seeing conditions (time scales of seconds) often encountered during the day-time (lake sites may be different).

The wavefront sensor must be able to lock on granulation and other solar structure, such as pores and umbral and penumbral structure.

The AO system shall correct residual (not corrected by active optics) optical aberrations and self induced and atmospheric seeing to the performance levels specified above. Mirror seeing or internal seeing in general must be avoided and any “residual” local seeing components must be correctable by adaptive optics, i.e., spatial scale of internal turbulence can not be smaller and temporal scales of internal seeing can not be faster than those of the atmospheric seeing.

The AO system shall be robust enough to perform during transparency fluctuations typically encountered in thin cirrus clouds.

Goal: The preferred location for the adaptive correction is the secondary, i.e., adaptive secondary; that means all instruments downstream from the secondary could be fed with an AO corrected beam without additional optical surfaces.

Implications for AO system design:

Figure 5 plots the Strehl ratio achieved for a 4m aperture as a function of the number of corrected modes (~DoF) and with r_0(500nm) as parameter. This calculation only considers the fitting error and the residual wavefront error due to limited bandwidth (200 Hz control bandwidth, Greenwood frequency 30 Hz). Wavefront sensor noise is relatively small for the solar AO case.

In principle, an AO system with order 400 DoF would meet the requirements for S>0.3 (good seeing) and S>0.6 (goal: S>0.7) (excellent seeing). However, the requirement for consistent image quality during varying seeing conditions will likely result in an AO system with significantly more DoFs (order 1000). This again will depend heavily on the site characteristics (fluctuations of r_0). Besides the fitting and bandwidth error terms other error terms (e.g., uncommon path, uncorrectable local seeing, calibration, instrument, etc.) have to be taken into account in the total error budget, which will further drive the AO towards a high-order system.

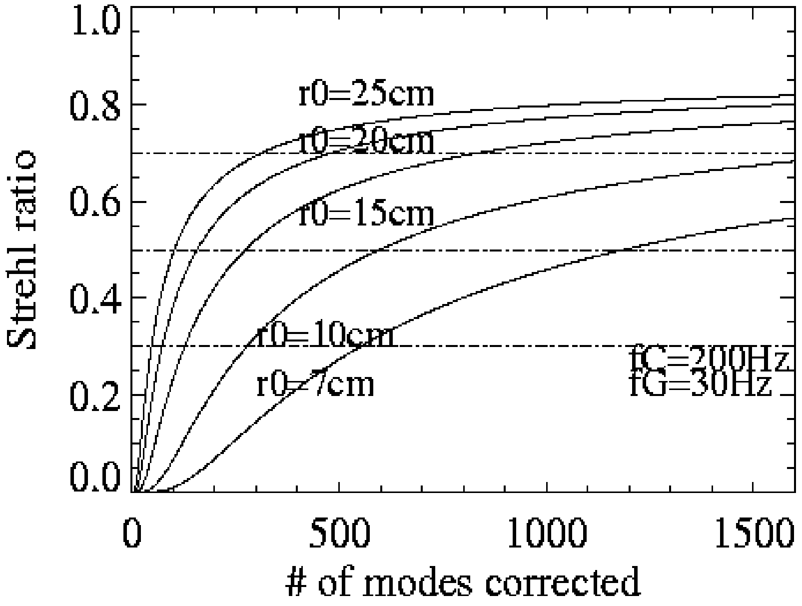


Figure 5: Strehl achieved as a function of order of correction and r_0.

Multi-Conjugate Adaptive Optics:

The ATST shall be designed in a way so that Multi-Conjugate Adaptive Optics (MCAO) can be implemented as soon as this technology has been successfully demonstrated on the Sun. A future ATST MCAO system shall achieve diffraction-limited resolution over a field of views of > 1.5 arcmin.

5.10. IR PERFORMANCE REQUIREMENTS:

Aperture:

ATST shall have a minimum of 4m un-obscured aperture. Goal: aperture as large as possible to achieve high resolution at thermal IR wavelength. The requirements specified above for scattered light, instrumental polarization and adaptive optics performance meet or exceed the IR performance requirements.

Emissivity:

The thermal emissivity of a good night-time IR telescope around K band is a few percent, which is difficult to achieve and requires gold mirrors and no other emissivity sources (like dust, M2 and spiders). The UKIRT 3.5m IR optimized telescope routinely measures Emissivity at 3.5 microns and achieves between 9-10%). Note that these numbers represent the fractional background signal compared to a room temperature blackbody. For nighttime IR observations this background dominates over the sky (at sites such as M. Kea or Haleakala).

For solar observations this is not obviously the case. The daytime sky at 4 microns is dark and is dominated by the K corona out to a solar radius or so. Thus, in general, the background tends to be dominated by the Sun and its scattered aureole and not thermal emissivity. We assume that the atmospheric "air glow" would be the biggest concern for coronal work in the thermal IR, for an off-axis telescope designed with good scattering properties in the visible.

The faintest IR source that drives the requirements is the corona; the emissive flux shall be less than the coronal emission in the band-pass being observed.

5.11. ENCLOSURE PERFORMANCE REQUIREMENTS

The primary function of an enclosure is to protect the telescope from the external ambient conditions, e.g., shielding against wind buffeting, baffling of stray light, controlling dust and other contamination. The enclosure shall perform these functions without compromising the top-level image quality requirements.

5.12. OPERATIONAL REQUIREMENTS

ATST SHALL BE OPERATED IN A WAY THAT ALLOWS COORDINATED AND SIMULTANEOUS OBSERVATIONS WITH SPACE MISSIONS AND OTHER GROUND BASED OBSERVATORIES.

5.13. SITE REQUIREMENTS

The ATST site requirements are described in a separate document (ATST Site Requirement Goals). In the following the desired ATST site characteristics are summarized. They have to be regarded as goals and no single site may exist that provides ALL of the desired characteristics. For example, a site may meet the requirements for good seeing conditions but only partially satisfy the coronal site requirements or vice versa. Feasibility issues also have to be considered. The necessary trade offs will be performed within the site selection process and will be based on science priorities and feasibility considerations.

6. INSTRUMENT REQUIREMENTS

6.1. INTRODUCTION

Designing an initial set of focal plane instrumentation is an important part of the overall design and development effort. There is an intimate connection between the telescope and focal plane instruments. Therefore, the instruments, at least partially, drive the telescope design, and vice versa. Some of the telescope designs influenced by instruments are:

- Optical configuration (e.g., f-ratio of optical beam)
- Location of instruments on telescope (e.g., image rotation, changing gravity vector)
- Auxiliary telescope optics (e.g., polarization calibration)
- Controls (e.g., close interaction between instruments and telescope)

Due to the close coupling of instrumentation and telescope, it is indispensable that the post-focus instrumentation and the telescope are designed as a system. A first step will be to design the initial or “first generation” suite of instruments. However, future instrument concepts have to be studied well enough so that their influence on the telescope design is well understood. Table 9.1 in the ATST proposal (http://atst.nso.edu/proposal/ , Appendix II) lists the instruments, along with preliminary specifications, that are envisioned to be deployed at the ATST during its life time. It is likely that scientific progress and new technology developments will result in additional instruments for the ATST.

6.2. APPROACH TO INSTRUMENTATION

There is a substantial difference in instrumentation between modern nighttime instruments and solar post-focus instrumentation. Typically, the number of instrument setups used on a solar telescope is about an order of magnitude larger than for a modern nighttime facility. Many solar observers build their optical setup specifically for a given observing run. Major advances in solar physics are often the result of studies of the same object with a different instrumental approach rather than from using the same instrument to look at various objects, which in general is the case for nighttime astronomy. “Canned” instruments that deliver a standard data product are the exception at “general purpose” solar telescopes like the DST. Typically, different instruments, e.g., spectrographs, narrow-band tunable filters covering different spectral lines or bands and imaging cameras are combined in a highly synchronized manner in order to gather a maximum of information. A common data acquisition system may be used to collect and preprocess the data from different instruments. This kind of diversity and flexibility of post-focus instrumentation are crucial for modern solar research and solar instruments tend to be designed as modules. For example, the same polarization analyzer may be used in front of a spectrograph or a narrow-band filter; a detector can be used to either collect imaging data or spectra from a high dispersion spectrograph.

Top Level Instrument Requirements:

- Simultaneous operations of various instrument combinations shall be possible.
- The telescope- instrument(s) system shall meet the top-level image quality requirements.
- Spectrograph based instruments shall achieve 2-dimensional spatial coverage either by scanning in one spatial dimension or by other means (e.g. IFU). Whether scanning is a function of the individual instrument(s) or a function that is performed by the telescope is TBD.

- Coordinated operation of ATST instrument(s) other ground based observatories and/or space missions shall be possible.

6.3. FIRST GENERATION INSTRUMENTS

The following table lists the initial set of instruments for the ATST. These first generation instruments are listed in the priority order agreed upon by the ATST Science Working Group. Instruments provided by international partners are not prioritized at this point. Detailed science requirements for these instruments can be found in the individual Instrument Science Requirements Documents (http://atst.nso.edu/swg/srd/).

Priority	Instrument	Fore-Optics	Dispersing System	Detector System
0	Broad-band imager	Phase Diversity	Interference Filters	Visible
1	Visible polarimeter	Visible polarization analyzer	Medium dispersion spectrograph	Visible or special
2	Near-IR polarimeter Disk and Corona	Near-IR polarization analyzer	Medium dispersion spectrograph	Near-IR
3	Visible tunable filter	Polarization Analyzer	Visible tunable filter	Visible
4	Near-IR tunable filter	Polarization Analyzer	Near-IR tunable filter	Near-IR
5	Thermal-IR Polarimeter & Spectrometer	Polarization Analyzer	Medium resolution, cold grating	Thermal-IR
6	Visible/near-IR high-dispersion spectrograph		Visible/near-IR high-dispersion spectrograph	Visible and near-IR
Swiss Contribution	UV-Polarimeter	Polarization modulation package	Visible spectrograph or narrow-band filter	ZIMPOL Detector System

Note: *The NIR polarimeter instrument(s) will perform disk observations as well as the 1 micron and 3.9 micron coronal observations (e.g. magnetometry).*

Request for Waiver

RFW Number: 0038

Date Requested:	**12-July-2013**
RFW Title:	**SRD Delivered Image Quality at 4.8 microns**
Contract No:	**N/A**
Requestor:	**Rob Hubbard**
WBS:	**1.2.3.1**
Document/Drawing Infringed Upon:	**SPEC-0001 SRD**
Summary of Issue:	**Unable to meet DIQ requirement at 4.8 microns on disk**
Next Higher Item Level Affected:	**N/A**
Items External to Contract Affected:	**Science performance**

Proposed Change and Justification:

The SRD Rev B includes a science case under 5.1.2.1 Seeing limited on-disk observations, Case 3, page 52 requires an encircled energy < 0.3 arcsec presuming only tip-tilt correction. This cannot be achieved without tip-tilt correction when the seeing is better than excellent, and with low-order Adaptive Optics correction using the Project's current definition of excellent seeing. The current ATST design and budget does not include this capability for the Cryo-NIRSP, which is the only first-generation instrument capable of observing at 4.8 μm. The optical feed for that instrument bypasses ATST's facility Wave Front Correction (WFC) system, and the WFC beam splitter does not pass 4.8 microns anyway.
Note that this does not preclude implementation as a future upgrade path.

Corrective Actions Already Attempted:
A fourth DIQ error budget was created for this science case and the requirements could not be achieved with realistic assumptions about the telescope and instrument performance without closed loop aO and AO.

Documents Attached: DIQ_Case4_CryoNIRSP.xls

Waiver, if granted, Adversely Affects:

Performance:	yes	**Reliability:**		**Cost:**	
Dimensions:		**Safety:**		**Software:**	
Weight:		**Maintenance:**		**Other Risk:**	

Impact if waiver not granted: The project will suffer a significant cost increase which is not currently in the budget or the risk register.

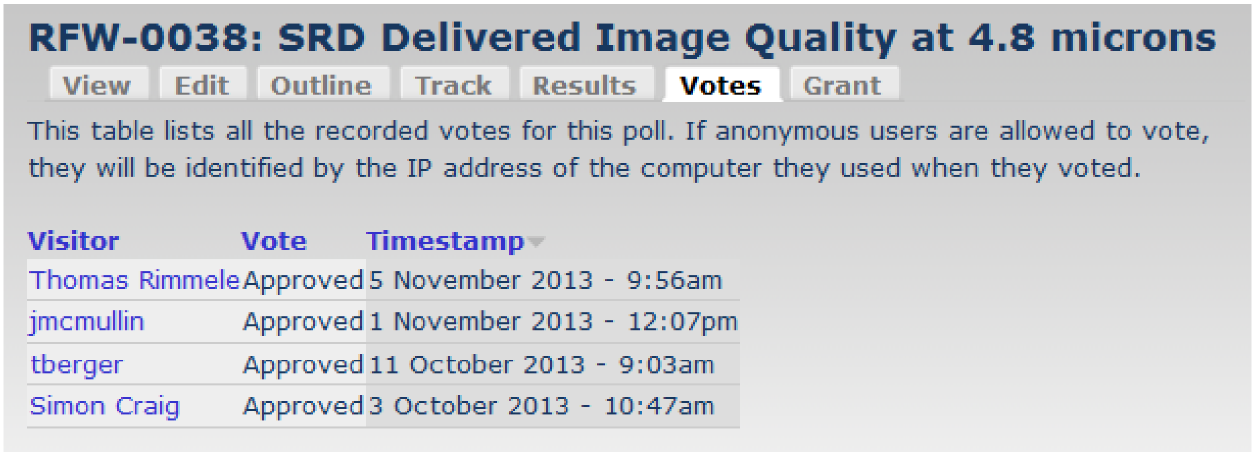
Request for Waiver

RFW Number: 0038

Concessions Offered: Future upgrade path during operations.

Please note: Both parties must sign to acknowledge acceptance of this waiver.

Contractor Project Manager		**Signature**	Thomas Berger Digitally signed by Thomas Berger DN: cn=Thomas Berger, o=National Solar Observatory, ou=ATST Project Science, email=tberger@nso.edu, c=US Date: 2013.11.06 16:03:04 -07'00'
		Date	
Work Package Manager		**Signature**	Robert Hubbard Robert Hubbard 2013.11.06 15:11:06 -07'00'
		Date	



RFW-0038: SRD Delivered Image Quality at 4.8 microns

This table lists all the recorded votes for this poll. If anonymous users are allowed to vote, they will be identified by the IP address of the computer they used when they voted.

Visitor	Vote	Timestamp
Thomas Rimmele	Approved	5 November 2013 - 9:56am
jmcmullin	Approved	1 November 2013 - 12:07pm
tberger	Approved	11 October 2013 - 9:03am
Simon Craig	Approved	3 October 2013 - 10:47am

ADMINISTRATIVE USE ONLY	
Change Control Board Decision: APPROVED	
Approval Date:	05-November-2013
Rejected Date:	