Solar Optical Instrumentation

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Outline

• Types of solar telescopes
• Good site, Dome design & Seeing
• Adaptive Optics
• Solar Guider
• Narrow band filter and imaging
• Coronagraphs
• New Telescopes: MAST, NLST
History of solar observations:

• In 1611, first telescope pointed to the sky by Galileo; Sun: Sunspots

• Scheiner (in Germany) in the same year also used a telescope view the Sun. Also observed by a Dutch Jesuit and in England.

• Dedicated solar telescopes from the beginning of 20th century on, first peak in the 40s.

Famous Carrington flare of 1859
Photons for Imaging

Light gathering power is proportional to square of the diameter

Collecting surface area = $\pi D^2 / 4$

in astronomy $f/D$ is called $f$-ratio or $F#$ where,
high $F#$: slow system
low $F#$: fast system
Solar Telescopes: Types

Could be **refracting or reflecting**

- A refractor (lens) reflects only a few percent of the light incident on it, absorbs very little, but transmits most of it.

- A telescope with a singlet lens suffers severe chromatic aberration due to the dependence of refractive index on wavelength, variation in focal plane for different wavelengths.

- A singlet lens could only be used for monochromatic work. (Traditionally H-alpha telescopes)

- A reflecting telescope is more suitable for spectrographic work, but the aluminium coated mirrors absorb 10 – 15% of the incident light, and heat up, resulting in bad image quality.
**Diffraction limit**

The resolving power depends on the wavelength of light being imaged and the diameter of the telescope objective.

For a circular objective, the circular diffraction pattern produced by the objective for a point source of light gives its first minimum as,

\[ \sin \theta = \frac{1.22 \lambda}{d} \]

where
- \( d \) - diameter of the lens
- \( \lambda \) - wavelength
- \( \theta \) - angular spread of the diffraction pattern from the primary max to first min.

For small \( \theta \), \( \sin \theta \approx \theta \), so the resolution is given by

\[ \theta = \frac{1.22 \lambda}{d} \text{ radians} \quad \text{or} \quad \theta = 252,000 \frac{\lambda}{d} \text{ arc-sec} \]

For a telescope, with aperture 0.5 m, the theoretical resolution limit is

\[ \text{limit} = \frac{252,000 \times 6302 \times 10^{-10}}{0.5} \quad \text{i.e. 0.317 arc-sec} \]

The angular diameter of the sun is \( \sim 32 \) arc-min, which is \( 2 \times 696,000 \) km

1 arc-second \( \sim 725 \) km on the sun.
Exercise

The diameter of the sun’s image produced by the telescope is given by, \( d = 2 \frac{f \text{rsun}}{A} \), where \( f \) is the focal length, \( \text{rsun} \), the solar radius and \( A \) the distance of the sun.

In terms of \( f\# \), \( d = 2 f\# \frac{D \text{rsun}}{A} \)

So, a large focal length telescope provides a comparatively large image of the sun but a large focal length telescope difficult to steer.

*Kitt Peak vacuum tower telescope* – long focal length

\[
D = 0.6 \text{ m} \quad f = 36 \text{ m} \quad f\# = \frac{36}{0.6} = 60 \\
\text{d} = 2 \times 60 \times 0.6 \times 696 \times 10^6 / (1.496 \times 10^{11}) = 0.333 \text{ m} (333 \text{ mm})
\]

*USO Coûde telescope* – short focal length

\[
D = 0.15 \text{ m} \quad f = 2.25 \text{ m} \quad f\# = \frac{2.25}{0.15} = 15 \\
\text{d} = 2 \times 15 \times 0.15 \times 696 \times 10^6 / (1.496 \times 10^{11}) = 0.021 \text{ m} (21 \text{ mm})
\]

So, the image size is governed by the focal length.
Lens Versus Mirror Objectives

- In small and medium size solar telescopes, lens objectives are generally preferred. Normally doublets to correct for the chromatic aberration.

- Singlet lens objectives are also used in the case of coronagraphs and special purpose solar telescopes dedicated for monochromatic observations, such as the twin 25-cm aperture telescopes of Big Bear Solar Observatory, the Udaipur Solar Observatory’s 25-cm refractor and many other dedicated telescopes.

- To reduce light and heat in the telescope tube, at some observatories, the objective lens is coated to yield a narrow bandpass of few hundred Angstrom wide, but then the observations are limited to a narrow spectral range.

- In mirror optics this problem of chromatic aberration is not encountered, however, the heating in the telescope tube, due to multiple reflections is a serious problem, for achieving high spatial resolution.
3 simple optical layout of solar telescopes

(i) & (ii) are refracting designs (iii) reflecting design
Studies of source region of CMEs from USO using telescope with a singlet lens

Solar Filament—Cold plasma hanging over solar surface

Solar Flares
High resolution solar telescopes

Large focal length solar telescopes provide bigger images, but it makes freely steerable solar telescopes inconvenient. So, special mirror arrangements are made to guide the sunlight into a fixed direction.

Heliostat and coelostat are examples of this kind of arrangements.

For obtaining bigger images short focal length objective could also be used, then by using relay optics a magnification is achieved. The diameter of the secondary image defines the ‘effective focal length’ of the telescope.
**The Heliostat**

In heliostat, a single flat mirror is used to reflect the light into a fixed ‘polar axis’ direction.

**The disadvantage of the**

heliostat is that the solar image rotates (15 deg/h) as Sun moves above the sky.

So, for long exposure observations the image rotation should be compensated. This could be done using extra optical elements such as Dove prisms or by rotating the whole post-focal instruments.
Coelostat is a two mirror configuration which avoids the image rotation. Here the primary mirror is mounted parallel and fixed to the polar axis.

A secondary mirror reflects the light to the desired direction. Here, both the mirrors rotate the image, but the two rotations compensate each other.

The angle of incidence on the coelostat mirrors are time dependent.

German, VTT telescope at Tenerife
Siderostat:

In the case of a ‘siderostat’ arrangement, a single mirror is alt-azimuth mounted and the movement of the mirror is transformed through a mechanical gear arrangement into an equatorial motion.

An 12-inch aperture siderostat is working for the last 100 years at the Kodaikanal Observatory. In all these systems the biggest advantage is that the image plane is fixed, therefore, large and heavy instruments such as big spectrographs, spectroheliographs, filters etc. can be coupled to the telescope.

In both heliostat and siderostat arrangements, the solar image rotates once in 24 hours around its centre, while in a coelostat the image does not rotate and is fixed. Therefore, coelostats are generally preferred.
Significant difference in requirements of solar & stellar observations:

• Site free of convection currents due to heating

• Design different

• Short, frequent exposures necessary

• Two-dimensional imaging provides better study

• High data cadence

• Synoptic versus high resolution observations of the Sun
Solar Seeing Problem

- The observing site should have minimum atmospheric turbulence, or in other words solar ‘seeing’ should remain good over long periods of time,

- that the telescope should have minimum thermal currents along the optical path within the telescope tube,

- the exposure time should be as short as possible, to ‘freeze’ the image otherwise disturbed by the seeing fluctuations,

- 2-dimensional and multi-waveband observations are generally required, taken preferably at a rapid rate.

Modern day Seeing problem is reduced by use of Adaptive Optics.
Selecting a solar observing site: Existing knowledge

Mountain sites versus island sites (in lakes/ocean)

Mountains are bad because of turbulent air
But these sites have less atmosphere.

Ideal situation scenario: Conduct seeing measurements at different sites with same instruments, preferably at same height for a long number of days.

General understanding: a site on a high mountain on an island surrounded by a large amount of water (lake/ocean?)

Eg. Big Bear Solar Observatory, California (lakes)
    Udaipur Solar Observatory, India
    Huairou Solar Observing Station, China

La Palma, Canary Islands, Spain: DOT, NSST (Ocean)
Tenerife, Canary Islands, Spain: VTT

The seeing scale ranges from 1 to 5, 1 is the best and 5 the worst.

These criteria take into account the “Image motion (IM)” at the limb, “Sharpness (S)” and “Quality (Q)”.

Image Motion (IM):

Qualitatively the magnitude of image motion can be classified as follows:
1. No image motion visible, neither at the limb nor on the disk,
2. Image motion detected only at the limb, no motion on the disk,
3. Image motion visible at the limb and on the disk,
4. Image motion almost prevents distinction between umbrae and penumbras, solar limb is strongly undulating or pulsating,
5. Image motion reaches diameter of small spots.
Sharpness (S):

1. Granulation is seen very conspicuously, and the structure of penumbral filaments can be recognised,

2. Granulation is well defined, the penumbrae are well visible, sharp boundaries between penumbrae and umbrae are seen,

3. Only traces of the granulation are visible, umbrae and penumbrae are well separated but seen without structure,

4. No granulation structure is detectable, umbrae and penumbrae are distinguishable only in large spots,

5. Granulation is not visible, umbra and penumbrae are indistinguishable even in large spots.
Because the rains are scanty in general, Udaipur site has more than 250 days of sunshine which allows to observe the Sun continuously (Successful GONG observations at Udaipur)
A solar guider consists of four photoelectric cells, which monitor the position of the telescope relative to the Sun and actuate servo motors, in the telescope drive to keep the solar image fixed at one place. If there is no flexure in the telescope, the image will remain fixed.

50 mm aperture, f/10 refractor useful for small telescopes.
A small image of the Sun is projected on a silicon quadrant cell, with an occulting disk that covers much of the image and allows only the outer edge of the Sun to be detected.

Lightweight piezo-electrically controlled ‘tip-tilt’ mirror arrangement is being effectively used for fast solar image stabilisation. Corrects for image motion and jumps but not for wavefront perturbations.
Adaptive Optics

Adaptive optics comprises of the measurement of wavefront perturbations, extracting the correction signals from these measurements, and application of this signals to a deformable mirror in order to restore the wavefront.

Schematic of the AO system for wavefront corrections
A wavefront sensor (WFS) that measures the wavefront aberrations.

The wavefront is typically sensed indirectly by, e.g., measuring wavefront gradients at a number of positions in a pupil plane.

An example of such a WFS is the Shack–Hartmann WFS (SHWFS), a wavefront corrector, such as a deformable mirror (DM) that corrects phase aberrations by introducing the correct, compensating optical path difference. The mirror surface is deformed by actuators located at the back of the thin mirror substrate also referred to as faceplate. 500-700 nm thick Silicon Nitride

a reconstructor, or a processing unit that computes actuator commands (e.g., voltages) from the WFS information. The processor unit typically also implements a closed-loop servo algorithm for driving the DM in the most effective way.
The main AO system components include

i) an image stabilization system: A CMOS camera and a tip-tilt piezo stage for correcting the global tilt of the wavefront

ii) a Shack-Hartmann wavefront sensor, comprising an array of micro-lenses, and a fast CCD camera (DALSA) 955 frames/s for sensing the local tilt,

iii) a 37 channel deformable mirror for correcting the local tilts.
Top panels show image motion in the open loop (OL) and closed loop (CL) in black and red, respectively. Bottom panels show the ratio of power spectra of closed to open loop.

Bayanna et al. 2008, 2012
A low order AO system correcting the atmospheric turbulence is developed at USO/PRL for high resolution imaging for the 50 cm MAST

Proto-type developed with a 15 cm telescope.

May 25, 2010 sunspot observations 20 x20 arc sec^2
Dutch Open Telescope at La Palma

MAST at Udaipur
Narrow Band Imaging

Narrow band filters are used to isolate a small spectral band in solar spectrum. The band pass of the filter could vary from few tens of $mÅ$ to few hundred of $mÅ$. 

(Top) Solar spectrum in visible showing the absorption lines.

(Middle) A blow up of a small segment from the spectrum showing the 6563 Ha chromospheric line.

(Bottom) Same as above, the green curve shows the profile of a narrow band filter.
Imaging in narrow band (H-alpha line)
Fabry-Perot (FP) etalon is a simple interferometer,

A simple FP etalon consists of two partially reflecting surfaces separated by a narrow cavity with optical separation $t$.

The light transmitted by the first surface is partially reflected and transmitted by the second surface and so on.

The transmitted or reflected rays coming out of the cavity combine constructively when the number of waves in the cavity is an integer for a particular wavelength.
The maximum transmission is obtained when the phase change $\delta = 2\pi m$ where $m$ is an integer.

*FP transmission profiles for different values of reflectivity $R$. When the reflectivity increases, constructive interference is more efficient and thus width of the pass band decreases.*
Fixed air space Etalons

Air cavity fixed with accurate low expansion spacers. Tuning is done by tilt, also by pressure (refractive index variation with pressure).

Tunable air space etalon

Here one of the plates is fixed and other one is mounted on three piezo stacks. By applying voltage to the stacks spacing between the plates can be changed.

Electrically tunable etalon

Similar to solid etalons, but the refractive index of the substrate could be changed by applying a voltage across the electro-optic substrate. Tuning by tilt, voltage (refractive index change due to applied electric field) and temperature.
FP as Narrow Band Filter

A blocking filter with a band-pass less than or equal to one FSR of the FP filter could be used to avoid all unwanted channels from the etalon. The combination acts like a narrow band filter.
Use of a narrow band filter for Doppler imaging. The solid and dash Hα line profiles show the unshifted and shifted wavelength positions. The red and blue curves show the filter profiles tuned to red and blue wings of the line profile.

Making two images, one each in the red- and blue wing of the line, the intensity difference between the two give an idea about the Doppler shift in the line and thus the line-of-sight velocity.
How to scan the spectrum using FP etalon?

Looking into the condition for maximum transmission, i.e.,

$$2\pi m = \frac{4\pi \mu d \cos \theta}{\lambda}; \quad m\lambda = 2 \mu d \cos \theta,$$

the transmission peak (for particular order $m$) can be shifted in wavelength,

i) by changing the cavity spacing $d$,
ii) by changing the refractive index $\mu$,
iii) or by changing the angle of incidence $\theta$
A typical spectrograph

• Consists of a slit, onto which the solar image is focused.

• Behind the slit, a collimating lens is placed to render the beam parallel, which then is followed by a

• dispersing unit, either a diffraction grating or a prism

• After the grating disperses the light, it is focused by a camera lens or a mirror and recorded digitally using a CCD chip.
Lens design

Mirror design

Collimator

Parallel light

Dispersed but parallel

Slit

Grating

Plate
In a simple Littrow system, a single lens performs the function of both collimator and camera,

The slit is at the focus of the Littrow lens, producing a parallel beam. This light is diffracted by the grating and refocused by the same Littrow lens at the focal plane, producing spectral lines as images of the slit.

This system has several advantages. It is very simple, symmetrical and convenient for the operation, it saves one optical component. But due to the chromatic aberration of the lens system, not all wavelengths can be focused at the same focal plane.
where \( n \) is the order, \( d \) is the separation of the grating lines, \( \lambda \) the wavelength, \( \theta \) the angle of incidence and \( \phi \) the diffraction angle. As \( n \) and \( \lambda \) occur as a product in the formula, the orders cannot be separated. 6000 Å in the first order falls at the same place as 3000 Å in the second order, and appropriate filters are used to separate these orders.

In the Littrow case \( \phi \approx \theta \) and \( \phi \) is constant,

\[
\frac{1}{f} \frac{d\lambda}{d\theta} = \frac{\lambda \cot \theta}{2f}.
\]
**Echelle Spectrographs**

It is sometimes interesting and necessary to observe the whole or a wide range of the solar spectrum as for flares, prominences and other transient phenomena.

Echelle gratings consist of a stack of thin glass plates (~ 40) arranged in a staircase type manner.
Relative intensity of the coronal light components and the sky as a function of solar distance (in solar radii). The relative intensity is normalized to the intensity at the center of the solar disk. (vander Hulst, 1953).
Figure 4-1: Conceptual diagram of the C1 coronagraph.
Lyot refractive internally occulted coronagraph

A1: entrance aperture
O1: objective lens
Oc: internal occulter,
FL: field lens
LS: Lyot stop
LF: Lyot spot
O2: transfer lens
FP: focal plane.
LASCO-C3 externally occulted 3.7 -32 solar radii fov
Advantages of mirror coronagraph versus lens coronagraph

1. no multiple internal reflections as in lenses,
2. no lens bulk scatter,
3. no problems due to potential browning and fluorescence of lens glass,
4. no chromatic aberration, allowing sharp focussing of the solar image on to the occultor simultaneously over the whole spectral regime,
5. no wavelength dependence of image dimensions both on the occultor and in the detector focal plane,
6. independence of atmospheric or vacuum refractive indices,
7. compact folded design possible,
8. capability of internal pointing correction by tilting objective mirror,
9. capability of "dynamic imaging" by tilting objective mirror, in order to improve spatial resolution,
Multiple coronagraphs needed to cover a large distance.
Figure 3-5: Fields-of-view of the three LASCO telescopes, and the region of overlap. Radius is given in $R_{\odot}$ for the various circular fields shown.
Udaipur Solar Observatory in the Lake Fatehsagar

Lake Observatory: Latitude 24.5  Longitude 73.7
Average seeing: 3-4 arc sec (5-4 r_o)
Best Seeing: 2 arc-sec
Multi-Application Solar Telescope (MAST):

The initial design led to the specifications for the telescope: 50 cm aperture.

Science Goals

• Understanding the magnetic field and velocity fields in small and large scale structure and active regions
• Study of fine structure of sunspots, granules & filaments
• Provide a long-time data base from MAST on solar cycle related problems like behaviour of magnetic stresses as a function of the epoch of the solar cycle.
• The topology and evolution of emerging magnetic flux regions leading to the solar activities such as flares and coronal mass ejections
• Quantification of helicity in solar active regions and their relation to explosive events

Main Components of the MAST
Optical, Mechanical Components
Thermal System, Dome
Installed by Advance Mechanical and Optical Systems (AMOS), Belgium at USO

An off-axis Gregorian afocal telescope, F#4

Clear aperture : 50 cm

Primary Mirror: Zerodur

Secondary Mirrors : SiC

**Highlights:**

- No scattered light due to secondary support structure, better PSF
- No central obscuration, more effective light collecting area, full pupil image plane available for wavefront sensing
- Polarimeter conveniently placed after secondary mirror
- Instrumental polarization due to multiple reflections can be modeled and corrected after calibration for the telescope
Mount: Alt-azimuth

Differential pointing accuracy: 0.5 arc-sec

Open loop tracking: 0.25 arc-sec for 10 min

Closed loop tracking: 0.1 arc-sec for 1 hour

M2 mechanism: Tip-tilt system

Mounted on a hexapod with correction capabilities for tilt, decentering and translation
Thermal Design

• Thermal Design takes care of the variation in the ambient temperature at the site

• Control of the solar flux falling on the opto-mechanical components and avoid any differential expansion of the mechanical structure

• Controls the temperature of the telescope with respect to the ambient air to limit the seeing degradation.

Highlights:

1. Sunshield protects the main telescope tube, fork from the direct heat.
2. M1 mirror is controlled by airflows with controlled temperature
3. M1 mirror surface kept within 1°C of the ambient medium
A collapsible dome made of tensile fabric, manufactured by Armatic Engineering of Bangalore (India) has been installed on the building housing the telescope.
MAST Telescope building

Observing Floor

Telescope Floor
Back-end Instruments for the MAST: In house Development at USO

Adaptive Optics: Tip Tilt + Membrane Deformable Mirrors (prototype successfully locked on a sunspot).

Narrow Band Imager: 2 F-P (CSIRO, Australia) in tandem giving combined spectral resolution of 114000 @ 617.3 nm

Polarimeter: Two LCVRs and a linear polarizer will be used for the measurements.

Spectrograph: Multi-Slit Spectropolarimeter with resolution of 25 mA in the 600 nm region.
AR 12192, 22 OCT. 2014, G-Band, FOV ~200 arc-sec (Test raw images)
Quiet Sun, 22 OCT. 2014, G-Band, FOV ~200 arc-sec (Test raw images)
AR 12192, 22 OCT. 2014, H-alpha, FOV ~170 x 225 arc-sec (Test raw images)
THE NATIONAL LARGE SOLAR TELESCOPE (NLST)
NLST, proposed by the Indian Institute of Astrophysics, is a 2-m aperture 3-mirror Gregorian on-axis telescope with an innovative design and low number of optical elements that will yield a high throughput with low polarization and high spatial and spectral resolution.

WHY 2-m?
- Scientific objectives:
  - High spatial resolution to resolve sub-arc sec magnetic elements;
  - High optical throughput (i.e. the number of photons per time on the detector and thus the signal to noise ratio which can be achieved);
- Use a tested design and technology (based on GREGOR)

MAIN SCIENTIFIC AIMS
- Magnetic field generation and the solar cycle (understanding the dynamo, origin and nature of the solar cycle);
- Magnetic coupling between the interior and outer solar atmosphere (dynamical processes and heating; magnetic network; sunspots);
- Local helioseismology;
- Measuring weak magnetic fields (e.g. internetwork, quiescent prominences);
- Thermal structure of the chromosphere;
- Energetic phenomena & Activity (e.g. active prominences, loops, flares & CMEs).
TELESCOPE FEATURES

• Aperture (primary mirror M1) : 2 metre with f/1.75
• Optical configuration : 3 mirror, Gregorian on-axis
• Field of view : 300 arcsec (200 arcsec AOcorrected)
• Final focal ratio of the system : f/40
• Wavelength of operation : 380 nm to 2.5 microns (visible to IR)
• Polarization accuracy : > 1 part in 10,000
• Adaptive optics : Close to diffraction limited performance
• Spatial resolution : < 0.1 arcsec at 500 nm

Focal plane instruments
• Broad Band Imaging System in Hα (656.3 nm), Ca II K (393.4 nm), CN band (383.3), G band (430.5 nm) and the continuum;
• Tunable Fabry-Perot Narrow Band Imager (500 – 900 nm);
• High Resolution Spectropolarimeter (380 – 1600 nm).

Current status
• 4 years of site characterization completed: Two world class sites identified (in J & K) with excellent seeing conditions for solar observations.
• A DPR has been submitted to the Indian Govt. -- formal approval is awaited;
• Fabrication of NLST expected to begin in 2014;
• First light expected in 2018.
Collage of instruments, clockwise from top right, (1) SDIMM and SHABAR, (2) sky radiometer, (3) all sky camera, (4) data acquisition facility at Merak, (5) AWS, and (6) micro thermal tower.
SCHEMATIC STRUCTURAL DESIGN OF NLST

OBSERVATION PLATFORM & LABORATORIES
Chromosphere observations

USO H-alpha

DOT H-alpha
28 October 2003, flare