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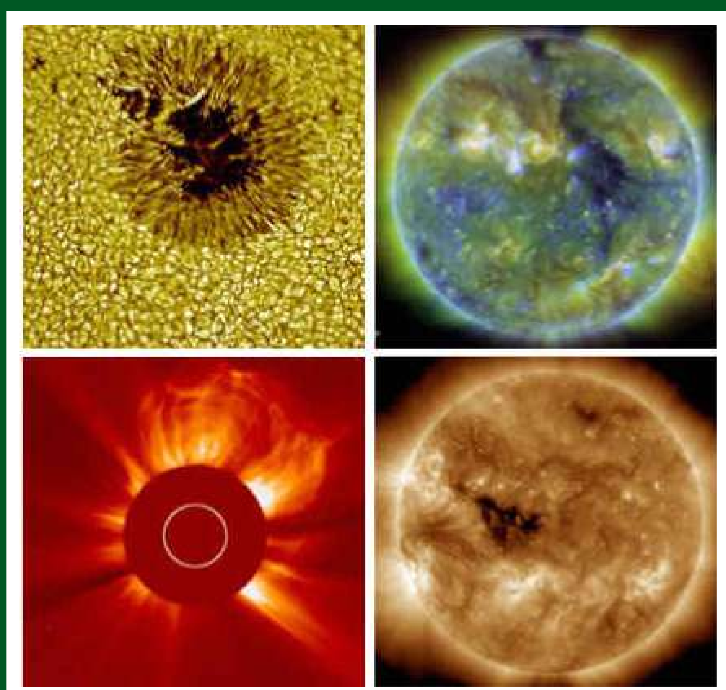

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Current trends in ground based solar magnetometry

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Continuous observations of the sun, over more than a century, have led to several important discoveries in solar astronomy. These include the discovery of the solar magnetism and its cyclic modulation, active region formation and decay and their role in energetic phenomena such as flares and coronal mass ejections (CMEs), fine structure and dynamics of the sunspots and small-scale organization of the magnetic flux in the form of flux tubes and so forth. In this article we give a brief overview of advancements in solar observational techniques in recent decades and the results obtained from the such observations. These include techniques to achieve high angular resolution, high spectral and polarimetric sensitivity and innovative new detectors. A wide range of spatial, temporal and spectral domains exploited by solar astronomers to understand the solar phenomena are discussed. Many new upcoming telescopes and instruments that are designed to address different aspects of solar physics problems are briefly described. Finally, we discuss the advantages of observing from the ground and how they can complement space-based observations.

Keywords: Sun; Magnetic fields; Polarimetry; Instrumentation: Solar activity

1 Introduction

Systematic ground based solar observations have been carried out now for more than a century. Some of the earliest measurements or recordings of sunspots date back to 3rd century BC in China. Later with the aid of telescope in early 16th century, first observations of the sunspots started in Europe. Finally, in 1849 systematic observations of the Sun started in Zurich observatory, where the drawings of the white light image of the sun were made and sunspot numbers and groups were recorded. These data are in use even today for understanding the behavior of solar cycles [1,2].

As a result of these early systematic observations many important phenomena were discovered. The eleven-year cycle of sunspot number as shown in Fig 1, for example, was found by Schwabe [3] using these records. Edward Maunder found that during 1645-1717 there were reduced number of sunspots, this period is now known as Maunder minimum, a period when cyclic activity of the sun almost disappeared. The spectroscopy of the Sun started in early 18th century when Josef von Fraunhofer first resolved dark absorption lines in the solar spectrum. Later in early 19th century the discovery of Zeeman effect led G E Hale to look at the spectrum of the sunspots, which eventually led to the discovery of the magnetic nature of sunspots.

Later Babcock and Babcock developed first longitudinal magnetograph, an instrument which made maps of magnetic field on the solar photosphere. These magnetographs used polarization optics and spectral isolation to derive the magnitude of longitudinal magnetic field. The magnetographic observations of the full solar disk revealed Hales polarity law, which says that the active regions emerge in bipolar groups such that the leading polarity in each hemisphere is opposite to each other. Further, 22-year magnetic cycle was also discovered by using these observations. The reversal of the sign of leading polarity of bipolar active regions in each hemisphere, as well as the sign of dominant polarity of the polar field after eleven years is termed as

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the 22 year magnetic cycle. These observations were crucial for the development of first physical models for solar cycle in terms of the solar dynamo mechanism.

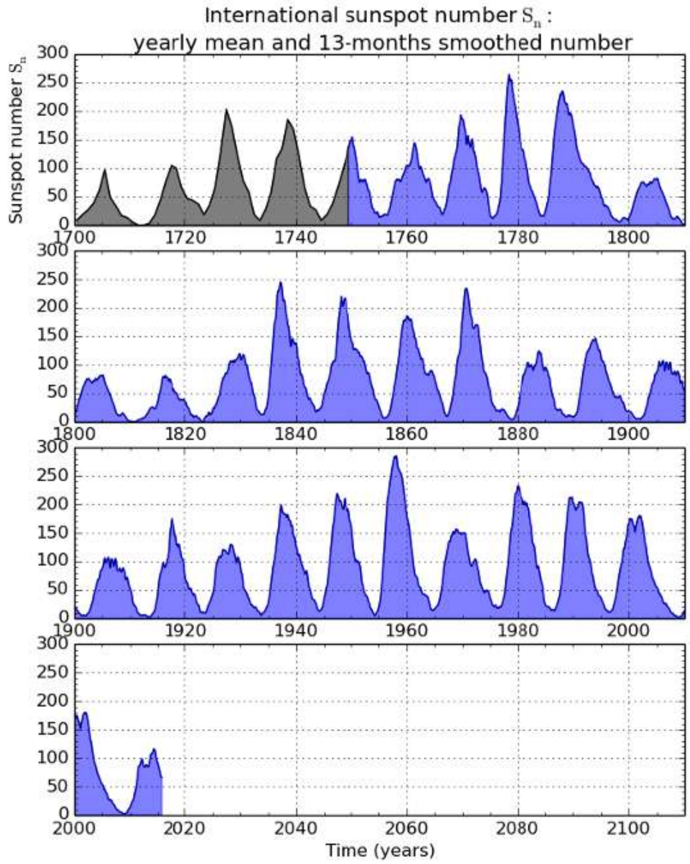


Fig 1. The 11-year cycle of the sunspot numbers since the beginning of 18th century depicting cyclic behavior of the solar magnetic activity. *Credit: http://sidc.be/silso*

Modern instruments routinely perform full Stokes spectropolarimetry of the solar atmosphere by employing different spectral lines, which form at different heights in the solar atmosphere, to infer the magnetic field and thermodynamic parameters in the line forming region. Highly sensitive digital detectors are being used with narrow band spectrometers (filter or spectrograph based) to derive detailed spectropolarimetric profiles over the observed region. Advanced polarization modulation and calibration techniques are used to make very sensitive and accurate measurements which are essential for reliable inference of magnetic fields.

The organization of the article is as follows: in section 2, we begin by presenting a brief overview of history of magnetic field measurements in the solar context and then layout current and future trends. Then we describe in section 3, the state-of-the-art in solar instrumentation. These include the large aperture telescopes that are on the horizon, the challenges of observing from ground in the presence of atmospheric seeing and methods to overcome it. Towards the end of section 3, we present state-of-the-art in spectroscopic and polarimetric techniques. Finally, in section 4 we present future outlook for improved solar observations and scientific breakthroughs expected from next generation of instruments.

2 Overview of Solar Observations

2.1 Solar Magnetism -- Past

George Ellery Hale (1868-1938) invented spectroheliscope in 1890s, using which he could make images of the sun in different wavelengths. He observed the solar atmosphere in chromospheric Hα line and found interesting whirly patterns, which gave him an impression of familiar iron filings organized around a bar magnet. In 1897 a Dutch physicist Pieter Zeeman had discovered that in the presence of magnetic field the spectral lines undergo splitting, an effect now known by his name. Hale looked at the spectrum of the solar lines formed in dark sunspots and found Zeeman splitting, thus establishing magnetic nature of sunspots. This was also the first discovery of magnetic field in an extra-terrestrial object.

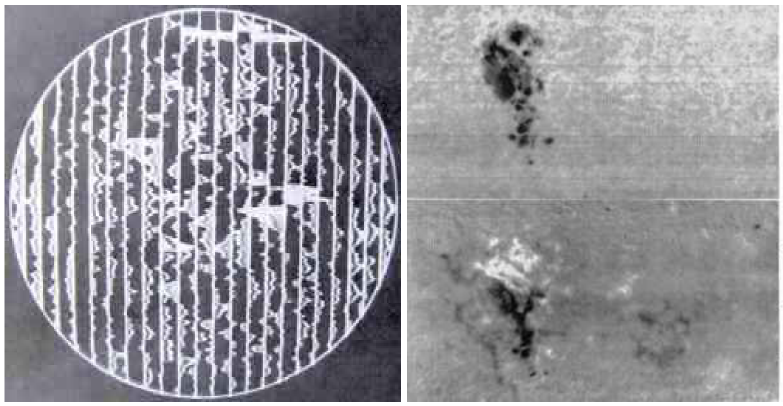


Fig 2. Left panel shows one of the first magnetograms of the sun obtained by H W Babcock in 1953. The deflections of the curves from vertical lines represent the strength of longitudinal magnetic field and direction of deflection shows the polarity of the field. In the right panel a two-dimensional magnetogram obtained by photographic subtraction method developed by R B Leighton is shown. The bipolar nature of active region magnetic field is clear from the black and white map of the longitudinal field component. (Adapted from Babcock [4] and Leighton [5], respectively)

Later Hale established the East-West polarity law of the active regions i.e., the polarity pattern of each bipolar region followed a pattern which was opposite across hemisphere, also this pattern reverses after 11 year cycle. This is known as Hale-Nicholson law. Later, Horace Babcock [4] developed first photoelectric magnetograph with enough sensitivity to make full disk maps of the Zeeman effect induced polarization. With this invention he could map the general dipolar (polar) field of the Sun and went on to propose a very popular model of the solar magnetic cycle known as "Babcock model". The Babcock type magnetograph became very popular and were replicated at various observatories around the world such as Crimea (*www.crao.crimea.ua*), KittPeak (*http://nsokp.nso.edu/*), Malta, Stanford (*http://wso.stanford.edu/*), and other observatories. This was largely one-diemnsional magnetograph as the slit of the spectrograph was sequentially scanned over solar disk to make maps of magnetic field. Next generation of two-dimensional magnetograph was developed by Bob Leighton in 1959 [5]. This method was based on subtraction of images taken in left and right handed circular polarized sigma components, which are shifted in wavelength due to Zeeman splitting. The two-dimensional magnetograms were very useful in studying the temporal evolution of magnetic field in solar active regions. The Fig 2 shows examples of the two types of magnetograms obtained by Babcock and Leighton, respectively.

2.2 Solar Magnetism -- Present

While classical magnetographs measured the spectral line polarization in the wings of the line [6, 7], later methods started employing so called spectropolarimeters. These instrument derived full spectral profiles of Zeeman sensitive lines in full state of polarization (Stokes I, Q, U, V). It provided detailed spectral profile shapes, allowing quantitative analysis that permitted higher precision measurements of the magnetic field vector. Sensitive measurements of the polarized spectral profiles are challenging especially in areas of weak magnetic fields, typically outside of sunspots or active regions. It may be noted that while longitudinal component of magnetic field is linearly proportional to circular polarization signal, transverse field is proportional to the square root of the linear polarization. Thus, it is difficult to measure the transverse field component as compared to the longitudinal field. However, transverse field component is very important for various studies of the solar active regions since the non-potential part of the magnetic fields due to electric currents can only be derived from transverse field component. A series of spectropolarimeters were developed at High Altitude Observatory (HAO), Boulder, USA, such as, Stokes-I in 70s, Stokes-II in 80s, Advanced Stokes Polarimeter (ASP) in 90s and finally culminated in high-resolution Diffraction Limited Spectropolarimeter (DLSP) in 2000s, all were deployed at National Solar Observatory's (NSO) Dunn Solar Telescope (DST; *http://nsosp.nso.edu/dst;* Fig 3) facility at Sac Peak, New Mexico. DLSP allowed flexible image resolution and could be tuned quickly to the diffraction limit of the telescope. Sample high resolution observations from DLST are shown in Fig 4.

Fig 3. (Left) NSO's Dunn telescope at the Sacramento Peak in New Mexico (USA) and (right) a high-resolution image of the Sun using the adaptive optics installed at the Dunn telescope.

In tandem with these improved spectropolarimetric observations the Stokes inversion codes were developed and refined at HAO to deduce reliable magnetic field vector from the fits to the observed polarized spectra. Several new results were obtained from these measurements, such as accurate field structure of large sunspots, as well as "fill fraction" of spatially unresolved structures. With development of ASP a new era in magnetic field measurements started as observing multiple lines at same time became possible with high angular resolution, while the inversion codes became more robust, allowing simultaneous fitting of multiple lines thus giving more robust estimate of magnetic field structure in the solar atmosphere. The space based Hinode Spectropolarimeter (SP) instrument draws heavily from the heritage of ASP. A few examples of other similar instruments developed in many observatories across the world are Multi-line Spectropolarimeter (MTR) at THEMIS, Tenerife Infrared Polarimeter (TIP), Spectro-Polarimeter for Infrared and Optical Regions (SPINOR), Facility Infrared Spectropoarimeter (FIRS), and VectorSpectroMagnetograph on SOLIS, to name a few.

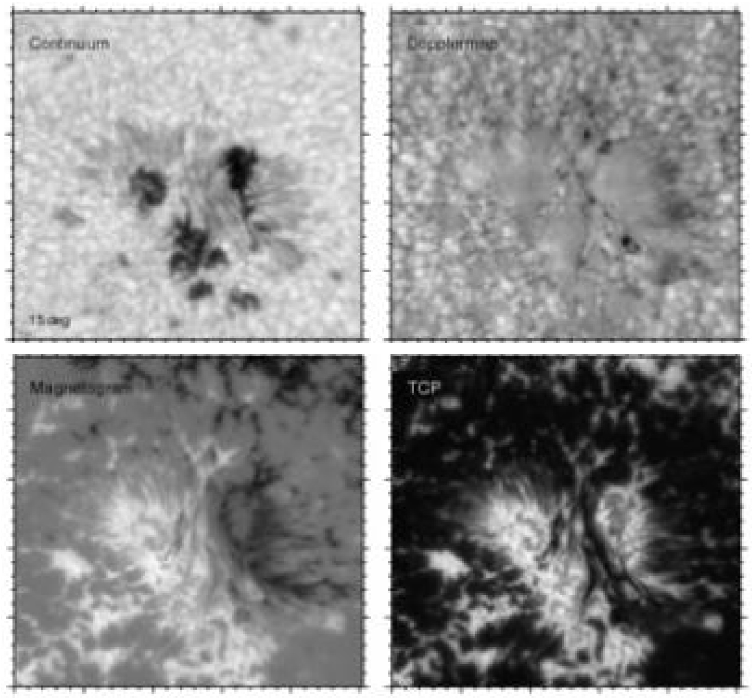


Fig 4. DLSP observations of a decaying complex active region NOAA 10956: From top left to bottom right, continuum intensity, LOS Doppler velocity, longitudinal magnetogram and total circular polarization (TCP) maps are shown.

2.3 Solar Magnetism -- Future

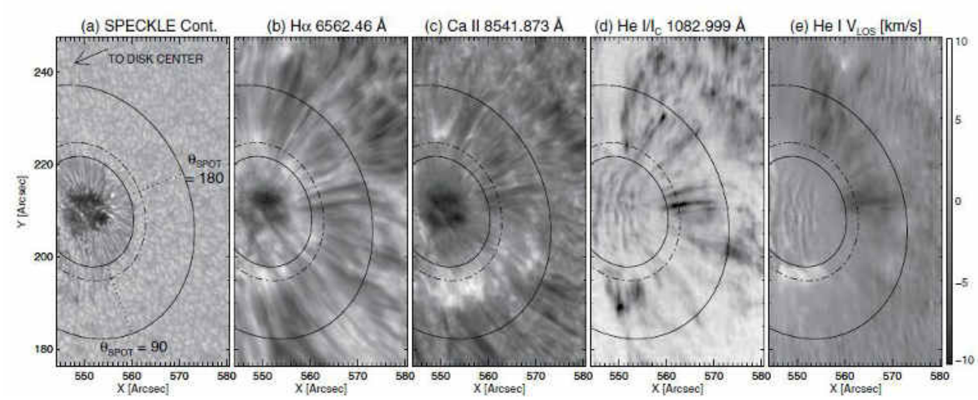
In order to achieve enough magnetic sensitivity, the measurements require large number of photons to be collected that are possible with large aperture telescopes. Due to high solar radiative flux the large apertures pose problem of heating, especially when used with shorter focal lengths. Thus, to avoid such problems, until late 1990s the typical solar telescopes were made to have large focal lengths resulting in large size of the telescopes. Such large telescopes cannot be easily moved so the telescopes were kept stationary and light feeds, such as heliostat or coelostat, were used to operate these telescopes. Some examples are McMath Telescope at Kitt Peak, Arizona, Dunn Solar telescope at Sac Peak, New Mexico, Vacuum Tower Telescope (VTT) at Tenerife, Spain. As a result of oblique reflections in the light feed mirrors, which changes during the day, a high level of background instrumental polarization is introduced in the beam which makes measurement of weak polarization signals of solar origin difficult. The polarization induced by the light feed mirrors can, however, be calibrated and accounted for in the measurements. The accuracy of the Stokes profiles is then limited by the accuracy achieved in the telescope polarization calibration.

With the advancement of technology in many areas, especially the fabrication of large aperture mirrors polished accurately under computer control, active thermal control systems, adaptive optics, image reconstruction methods and sensitive and fast detectors, it has become possible to realize large aperture telescopes. The 4-metre aperture Daniel K. Inouye Solar Telescope (DKIST, Fig 5) being developed by NSO, to be installed at Haleakala, Hawaii, is the culmination of several latest technologies. Latest updates and more details on the project DKIST can be found online at *dkist.nso.edu*.

In recent years there has been thrust in understanding the nature of chromospheric, transition region and coronal fields. Various attempts are being made. On one hand the new diagnostics are being exploited such a modification of scattering line polarization via Hanle effect near the solar limb. Hanle effect leads to a detectable reduction in the amount of scattering polarization in spectral lines in the presence of magnetic field. Hanle effect is complementary to the Zeeman effect in the sense that while the latter is sensitive to strong magnetic fields the former is sensitive to weaker fields, i.e., the regime in which the magnetic splitting of sublevels is of the order of natural line width. Hanle diagnostics, however, require measurements of polarization signals with very high signal-to-noise ratio (SNR), a few 10^{-5} of continuum intensity. For more details on the physics of Hanle diagnostics and modification of scattering polarization see reviews by Trujilo Bueno *et al* [8], Landi [9], Stenflo [10].

Fig 5. An artist view of the DKI Solar Telescope being built in Hawaii, USA. Courtesy: NSO (USA)

Further, full Stokes measurements in the chromospheric lines is being carried out with the goal of inferring 3D structure of magnetic field vector in solar active regions and filaments. There are not as many lines available for chromospheric measurements as in photospheric case. Some of the lines that have been used in past decade are He I 1083nm, Ca II 854.2 nm, Na D1, Mg b1,2, H-alpha, H-beta, and He D3. In particular, He I 1083nm diagnostics look very promising as has been recently very successfully applied to FIRS observations of superpenumbral fibrils around sunspot by Schad *et al* [11]. These observations were analyzed with advanced inversion tools which model Hanle and Zeeman effects together to infer magnetic field vector. Their observations and results, reproduced in Fig 6, show that the superpenumbral fibrils indeed follow the magnetic field direction within an error of +/- 10 deg. Further, they also found evidence for flows along fibrils that suggest siphon flow like mechanism at play.



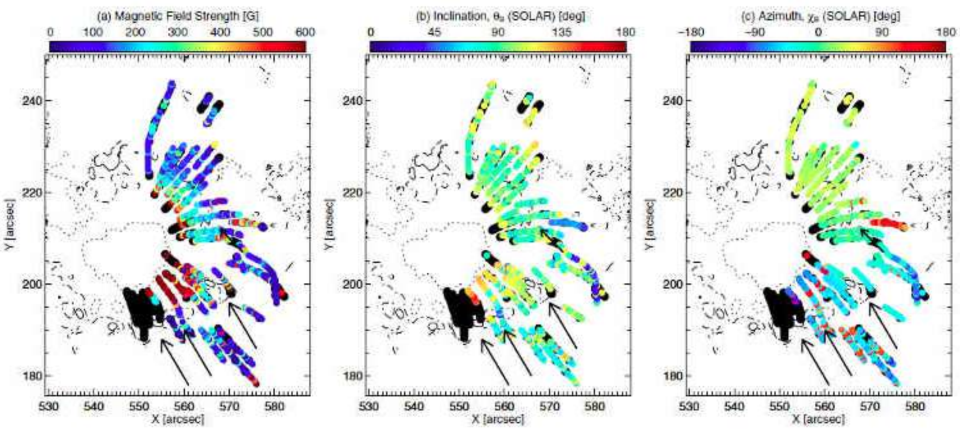


Fig 6. Top panels show NOAA AR 11408 observed by FIRS and IBIS on 2012 January 29. (a) Speckle reconstructed broadband channel image from IBIS instrument, (b) IBIS H-alpha intensity image, (c) IBIS Ca II intensity image, (d) FIRS map of He I relative intensity i.e., I/Ic. € He I Doppler velocity corrected for orbital motions and solar rotation Bottom panels show maps of magnetic field vector of superpenumbral fibrils inferred from the He I triplet (adapted from Schad *et al* [11]). The black data points show locations of bad fits to the spectra, while contours show inclination angle for values of 135° (dotted), 90° (dot-dashed) and 65° (solid). The inclination and azimuth values are in local solar refrence frame. The vector directions of many fibrils have a 180° Hanle ambiguity, which is solved using potential field method. Black arrows show region of plage with polarity opposite w.r.t the spot. (See Schad *et al* [11] for more details)

3 State of the Art in Solar Instrumentation:

3.1 High Angular Resolution

3.1.1 Large Aperture Solar Telescopes:

Challenges for High-angular resolution from Ground: ground-based observations typically suffer from atmospheric seeing. Atmospheric seeing characterizes the extent to which the atmospheric temperature fluctuations cause variation of refractive index and is used to describe the extent to which phase distortions in the transmitted wavefront distort the astronomical images. It should be noted that daytime astronomical seeing is different from the nigh time seeing. During daytime the heating of the ground due to solar radiation causes warm air currents to rise up and cause additional fluctuations in the refractive index close to the ground. For this reason, solar telescopes are preferred to be located on top of high towers, to avoid ground heating caused turbulence, or near a large body of water such as in a lake as shown in Fig 7 (Udaipur Solar Observatory, India or Big Bear Solar Observatory, BBSO, California, USA) or near sea (Swedish Vacuum Solar telescope, SVST, La Palma, Canary Islands, Spain). With the pioneering concept of open air telescopes successfully demonstrated by Dutch Open Telescope (DOT) at La Palma, such concept has become quite common in recent times. In open air design the telescope's mechanical structure is specially designed to withstand strong winds while taking advantage of cooling action of air which flushes the telescope structure and optics and keeps their temperature close to ambient and thus minimizes telescope's own seeing caused by temperature differential between telescope structure and ambient air.

New telescopes such as GREGOR *(http://www.aip.de/groups/gregor/index.html*; [12]), DKIST (*dkist.nso.edu*; [13]), Multi Application Solar Telescope (MAST; *https://www.prl.res.in/~uso/ mast/mast. html*; [14]) are designed to have open structures in the sense that these employ foldable dome or dome with ventilators to benefit from ambient air flushing/cooling. Active cooling is still required for primary mirror as well as the aperture stop at the prime focus, which is designed so as to absorb (via internally flowing coolant) the concentrated solar flux falling on it.

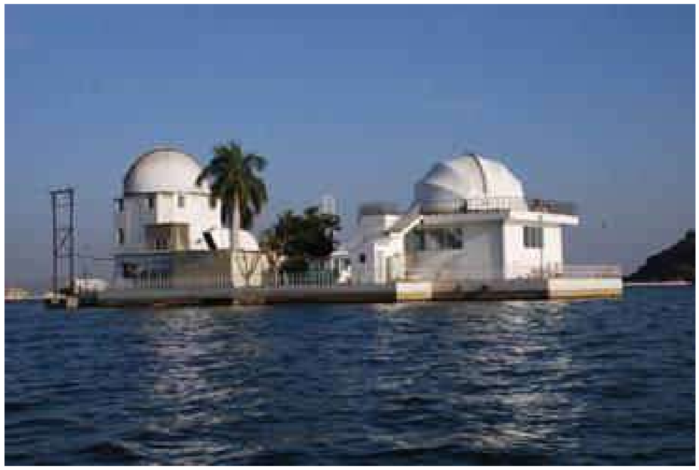


Fig 7. Udaipur Solar Observatory (USO) situated in the middle of a lake in Udaipur (India). Source: *https://www.prl.res.in/~uso/*

Even after minimizing the effect of internal or telescope seeing the ground layer turbulence and upper atmosphere seeing lead to distortions in the wavefront that need to be corrected to achieve diffraction limited performance of these large aperture telescopes. Here one needs optical systems that are called adaptive optics systems which help in correcting the wavefront errors due to atmosphere by actively sensing the wavefront and compensating the errors by flexible mirrors such as tip-tilt and deformable mirrors.

3.1.2 Adaptive Optics (*AO*)

The large aperture telescopes, which are essential for achieving high sensitivity in measurements by providing large number of photons at decent resolutions still need to be corrected for cumulative effects of atmospheric (near ground as well as in upper atmosphere) and telescope seeing. As an example, we show the image of an active region with and without adaptive optics. It can be seen that the quality of the image can be significantly improved if the AO system is used.

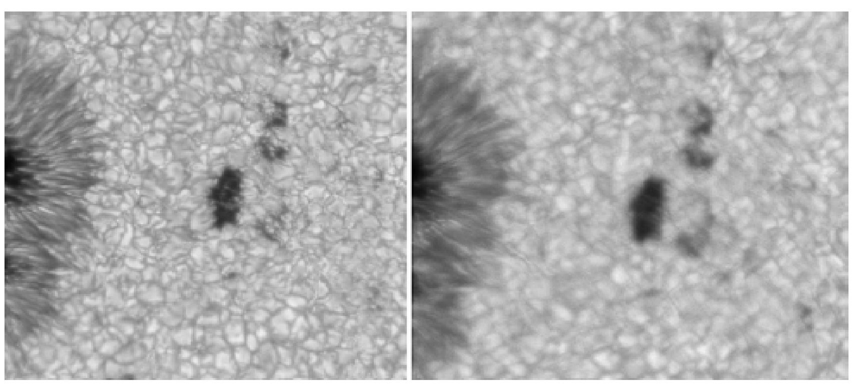


Fig 8. The image of an active region with (left) and without (right) AO correction is shown. The field-of-view is 45×45 arcsec with a wavelength of 550 nm. The AO was locked onto the dark structure, pore, in the centre of the field-of-view (adapted from [15]).

A conventional adaptive optics system can be understood in terms of following components: (i) wavefront sensing system: a system, in most cases a Shack Hartmann type wavefront sensor, which is used to estimate the wavefront distortions in near real time, and (ii) correction optics: this can be further composed to two sub-components (a) tip-tilt system, which basically works to correct lowest order distortions due to atmospheric seeing, and deformable mirror (can be bimorph type or segmented mirror type): this system is used to correct for higher order aberrations in the wavefront such as coma, astigmatism etc.

3.1.3 Multi-conjugate adaptive optics (*MCAO*)

The angular field-of-view over which the AO corrections are valid is not unlimited. Practically the AO corrections deteriorate with angular distance from the central point of lock in the wavefront sensor (WFS) field, this is called anisoplanatism and it depends upon aperture size of the telescope, the profile of turbulence, seeing or Fried's parameter r_0, and wavelength of observation [13]. This places limits on the FoV over which high resolution observations can be achieved. The limitation is severe in studies which are focused on active regions scales which are or the order of 6×6 arcmin square. To remedy this limitation a more complex system is used which is called multi conjugate adaptive optics (MCAO) [16, 17]. MCAO is basically an extension of the original AO concept. It allows correcting for the turbulence in three dimensions by employing more than one deformable mirror (DM). Each DM is optically conjugated to a certain height in the atmosphere above the telescope. The benefit of MCAO is reduced anisoplanatism, hence an increase in the corrected FoV.

3.1.4 Post-facto Image Reconstruction Techniques

The AO systems can correct the effects of atmospheric distortions, however, the correction is not perfect and residual distortions still remain. The AO corrections work better when working at longer wavelengths, which is why large aperture telescopes like DKIST are primarily targeting infra-red wavelengths. In order to achieve a uniform image resolution over the observed field-of-view post-facto processing techniques are used. These methods include speckle interferometry [18, 19], phase-diversity techniques [20], multi-frame blind deconvolution (MFBD) [21], and multi-object multi-frame blind deconvolution (MOMFBD) [22]. Woeger and Luhe [23] have shown that the combination of AO and post processing techniques leads to uniform diffraction limited resolution over large FoV. With the advancement in parallel computing power of processors post facto processing is becoming more routine. One limitation of postfacto techniques is that it can only be applied to the 2D imaging systems and not to sequential scanning systems like spectrographs where the pseudo-image is constructed by scanning the 1D slit across the FoV. It is therefore desirable to have best of both the worlds by having a reflective slit such that while the 1D scanning is being performed the reflection of the slit is fed to a filtergraph for simultaneous observations. This way one can get continuous complementary information in time, space and wavelength domains. This is specially important when studying dynamic events such as flares or highly dynamic layers of the solar chromosphere.

3.2 High Spectral Resolution

Narrow band tunable filtergraphs: Traditionally the narrowband (sub-Angstrom) filtergrams of the Sun obtained in Hydrogen alpha line at 656.3 nm, have been used as the so-called "poor man's magnetograms". This is so because the chromosphere appears highly structured in this line, reminiscent of iron filings near a bar magnet. These filtergram are easily obtained using either interference filters, tunable birefringent filters or Fabry-Perot etalons. The birefringent filters of both Lyot and Solc type have been demonstrated and have been used quite successfully at various observatories. The ability to rapidly tune the bandpass used to be typically slow and inaccurate in these filters because of the mechanical nature of tuning. However, in the past decade or so fast and accurate electro-optic retarders such as nematic liquid crystal variable retarders have replaced the fixed retarders and tenability has become faster and more repeatable than earlier. An example of one such filter is the visible tunable filter (VTF) in Full-disk Patrol (FDP) instrument in the SOLIS suite of instruments.

For even faster tunability and accuracy Fabry-Perot etalons based on piezo-crystals are used. In these filters the highly polished (lambda/200) highly reflective ($R > 0.95$) mirrors, mounted on piezo stacks forms the etalon cavity. The cavity spacing and parallelism is actively sensed using three gap-sensing capacitance micrometers and is used to maintain the cavity spacing and parallelism via servo controller. These filters can be tuned on microsecond time-scales and are highly repeatable. Further, the range of tuning of the cavity spacing can be made quite large if required, thus giving the filter a large free-spectral-range (FSR). The state-of-the-art in these type of filters is typically FSR of 4-5 Angstroms, Finesse (a measure of shape of the transmission profile given by ratio FSR/FWHM) of 50 and FWHM of ~100mA. Further, with combination of two more more etalons in tandem or in double pass configuration the finesse can be increased significantly. The largest size of such etalons that are successfully used in astronomy is about 100 to 150 cm diameter aperture (ISOON and Canary islands). However, for use with large aperture telescopes in future such as DKIST one needs to make even larger aperture etalons. Currently, one such project is underway at KIS Freiburg where an etalon as large as 20 cm is being designed and built [12]. This would be the largest etalon of this kind ever built.

3.2.1 High Resolution Multiplexed Spectrographs

The spectral resolution of conventional grating based slit spectrographs is difficult to achieve in filter based spectrometers, if not impossible. Even then the snapshot nature of spectra obtained by spectrograph is more desirable than the spectra from filter based spectrometers usually obtained by scanning in time, especially when studying dynamic events or when variable seeing is a concern. However, conventional 1D spectrometers have less appeal when information is needed over a larger or 2D FoV simultaneously, again to study dynamic small scale features, which is exactly what one is interested in observing with the next generation of large telescopes. Thus, one somehow needs to obtain simultaneous high resolution spectrograph observations over 2D FoV.

Traditionally one can use one of the many existing techniques such as Bowens image slicer, where a stack of glass plates is designed in such a way that the 2D FoV is converted optically to 1D and then fed to spectrograph slit to obtain simultaneous spectra over 2D FoV. However, the FoV can be quite limited with such slicers [24]. Other way is to use fiber array such that 2D FoV is imaged onto a 2D fibre matrix which are then translated geometrically to a 1D array and fed along the slit of the spectrograph, thus obtaining simultaneous spectra over 2D FoV [25]. Here the challenge is to get the geometry of fibre alignment correct and also the polarization response of fibres. Yet another method is to use multi-slit spectrograph where narrow parallel slits are used to feed the spectrograph and an order sorting filter is used to prevent adjacent spectra from overlapping on the detector. An innovative concept under development is the so called microlens spectrograph [22] being developed at Max Planck Institute for Solar Physics, Goettingen, Germany. It is basically a version of multi-slit spectrograph, however, instead of multiple slit there are multiple pinholes fabricated as a mask, which is used as multislit and the mask is oriented to avoid overlapping of spectra corresponding to each pinhole.

3.3 High polarimetric sensitivity and accuracy

Sensitive Polarimetry: The sensitivity of any polarimeter depends upon the number of photons collected while the accuracy depends upon the extent to which the system is calibrated. In terms of sensitivity then the larger the aperture of telescope the larger the sensitivity in a given amount of observing time or exposure. The largest aperture solar telescope in near future will be the 4 meter aperture DKIST. Compared to current meter-class aperture telescopes it will have 16 times more collection area, and thus when DKIST is operated at the diffraction limit of meter-class telescopes of today, it would provide a factor of 4 more sensitive observations with the same exposure time. In other words the observations with same sensitivity as provided by meter-class aperture telescopes could be obtained by DKIST in $1/16^{th}$ of the time. For example, a typical 10-minute slit scan of a sunspot could be done in about 40 seconds. On the other hand, the amount of photons at the diffraction limit of a given telescope, per unit time remains unchanged. Therefore, as one tries to observe at the diffraction limit of the 4 m DKIST, one does not gain in terms of photons. In fact, due to the rapid evolution of solar features at smaller scales the amount of exposure time that one can afford becomes smaller too, and thus leads to even smaller number of photons per diffraction limit per unit time, as compared to the meter-class telescopes. However, one can build high signal-to-noise ratio observations by combining individual observations of identical features, such as by co-adding data for many penumbral fibrils to derive their average properties. Thus, for narrowband observations the DKIST will have an advantage when observing above diffraction limit, while for broadband observations high-resolution data at high time cadence will be easy to obtain.

The accuracy of the polarimetry depends upon careful calibration of the optics that can lead to instrumental polarization before the modulator and characterizing the response matrix of the modulator itself. These require careful laboratory characterization of the components as well as schemes for routine online calibration of the optical train by inserting calibration optics such as a linear polarizer and a retarder, preferably at multiple wavelengths and multiple orientations. Performing such calibrations regularly is desirable because with time the properties of the mirror coatings as well as that of liquid crystal modulators can change. Further, dual beam modulator designs are known to provide an excellent way of tackling the seeing induced spurious polarization in sequential measurements. Also, the dual beam method allows efficient use of the available photons without rejecting 50% of the photons, as in the case of single beam techniques.

4 Future Outlook

The upcoming large aperture telescope DKIST is expected to provide the observations with highest angular resolution so far. Such observations will provide us important clues about the highly intermittent magnetic fields observed at the solar surface, their possible origin in small scale dynamo, and their dissipation and connection with coronal heating. Further, we may also understand how evolution of small scale magnetic field lead to disruption of large scale magnetic configurations causing flares and coronal mass ejections.

When DKIST is used at a modest spatial resolution of currently available ground based telescopes such as GREGOR, NST or SVST, the 8-16 fold increase in light collection power of DKIST will push the sensitivity (SNR) of photon starved measurements by a factor of 3 - 4. This will be especially beneficial for sensitive polarimetric measurements.

For large-scale as well as long-term studies of the Sun have improved synoptic measurements as envisaged by the development of SPRING network [2, 26]. The SPRING network aims to provide a global infrastructure to continuously measure sun's magnetic and velocity field over the full disk at different wavelengths. Such observations will be very useful for driving the models used for space weather predictions. Also, these multiline observations may benefit many areas of solar physics research such as, coronal force-free field extrapolations, flare research, local helioseismology, wave-propagation in solar atmosphere etc. Further, the long-term evolution of solar magnetic fields over 22 year magnetic cycle will benefit tremendously due to continuous nature of such observations from a global network.

SPRING observations will also provide a baseline of continuous multi-line observations very essential for coordinated observing campaigns between multiple large aperture telescopes across the world as well as space based telescopes, which have typically small field-of-view and different observing time windows, therefore need baseline observations for contextual information as well as for coordination, co-alignment etc.

References

1. Foukal P, *Astrophys J*, 815(2015)9.
2. Elsworth Y, Broomhall A -M, Gosain S, Roth M, Jefferies S M, Hill F, *Space Sci Rev*, 196(2015)137-166.
3. Schwabe M, *Astron Nachr*, 21(1826233-236.
4. Babcock H W, *Astrophys J*, 118(1953387-396.
5. Leighton R B, *Astrophys J*, 13(1959366-380.
6. Hagyard M J, Cumings N P, West E A, in Solar Physics and Interplanetary Travelling Phenomena, (eds) C de Jager, B Chen, (Beijing: Science Press), 1985, 121.
7. Wang H, Zirin H, Patterson A, Al G, Zhang H, *Astrophys J*, 343(1989)489-493.

8. Trujilo Bueno J, in Advanced Solar Polarimetry -- Theory, Observation, and Instrumentation, (eds) Michael Sigwarth, Astronomical Society of the Pacific, 236(2001)161-191.
9. Landi, D E, Landolfi M, *Ploarization in spectral lines*, (Astrophysics and Science Library #307 Kluwer Academic Publishers, Dordrecht), 2004.
10. Stenflo J O, in Solar polarization, (eds) K N Nagendra, J O Stenflow, *Astrophys Space Sci Lib*, 243(1999)1-16.
11. Schad T A, Penn M J, Lin H, Tritschler A, *Sol Phys*, 290(2015)1607.
12. Schmidt W, von der Lühe O, Volkmer R, Denker C, Solanki S K, Balthasar H, Bello Gonzalez N, Berkefeld Th, Collados M, Fischer A, Halbgewachs C, Heidecke F, Hofmann A, Kneer F, Lagg A, Nicklas H, Popow E, Puschmann K G, Schmidt D, Sigwarth M, Sobotka M, Soltau D, Staude J, Strassmeier K G, Waldmann T A, *Astron Nachr*, 333(2012)796-809.
13. Rimmele T, McMullin J, Warner M, Craig S, Woeger F, Tritschler A, CassinI R, Kuhn J, Lin H, Schmidt W, Berukoff S, Reardon K, Goode P, Knoelker M, Rosner R, Mathioudakis M, DKIST Team, *IAU General Assembly*, 29(2015)2255176.
14. Mathew S K, in Solar polarization 5, (eds) S V Berdyugina, K N Nagendra, R Ramelli, *Astron Soc Pacific Conf Ser*, 405(2007)461-66.
15. Rimmele T R, Marino J, *Liv Rev Sol Phys*, 8(2011)2.
16. Beckers J M**,** ESO Conference on Very Large Telescopes and their Instrumentation, 2(1988)69-703
17. Rigaut F J, Ellerbroek B L, Flicker R, in Adaptive optical systems technology, (ed) P L Wizinowich, *Procd SPIE*, 4007(2000)1022-1031.
18. von der Lühe O, Dunn R B, *Astron Astrophys*, 177(1987)265-276.
19. Keller C U**,** von der Lühe O, *Astron Astrophys*, 261(1999)321-328.
20. Löfdahl M G**,** Scharmer G B, in Image reconstruction and restoration, (ed) T J Schulz, *Procd SPIE*, 2302(1994) 254-267.
21. Löfdahl M G, in Image reconstruction from incomplete data, (eds) P J Bones, M A Fiddy, R P Millane, *Procd SPIE*, 479(2007)146-155**.**
22. van Noort M, Rouppe van der Voort L, Löfdahl M G, *Solar Phys*, 228(2005)191-215
23. Wöger F, von der Lühe O, *Appl Opt*, 46(2007)8015-8026**.**
24. Pierce A K, *Publ Astron Soc Pacific*,77(1965)216-217.
25. Lin H, Versteegh A, in Ground-based and airborne instrumentation for astronomy, (eds) I S McLean, M Iye, *Procd SPIE*, 6269(2006)62690.
26. Hill F, Thompson M J, Roth M, *Space Weather*, 11(2013)392-393.

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