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Solar granulation and speckle interferometry

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Abstract. During the last twenty years, quite a good number of applications of speckle interferometry and imaging have been made to the study of solar granulations as well as solar activity. We present here a brief status of various aspects of the same.

Key words : speckle interferometry—solar granulation

1. Introduction

Since two decades, speckle interferometry, speckle imaging and related techniques are widely utilized to study stellar objects and systems. In contrast to this, however, their applications to solar study have been on a low key, although these very twenty years have seen quite a number of approaches being applied successfully to the investigations of the quiet as well as the active sun.

von der Luhe & Zirker (1988) opine that the presently achievable resolution can be increased by about one order of magnitude by interferometry. Besides offering photometric capability, there is no critical new technology needed for developing speckle interferometry as a high resolution tool in solar astronomy. But there are some areas that require technical development, more so when we talk of indigenous fabrication and assembly.

In the present paper, in section 2, we have attempted to compile, and critically comprehend the available solar (speckle) results and efforts. Section 3 deals briefly with the physical aspects of the science of solar granulations (SG), with stress on the current astrophysical fields of interest and how in future they can be better unravelled with speckle techniques.

2. Historical review

Labeyrie (1970) introduced speckles into optical astronomy while Harvey & Breckinridge (1973) initiated a branch for solar speckle interferometry, detecting spatial frequencies of about four cycles per arcsec in sunspots with the McMath solar telescope. Aime (1974) measured the average squared modulus of atmospheric lens modulation transfer function (MTF) which provided the reference source for calibration. Harvey & Schwarszchild (1975) conducted photoelectric speckle interferometry of SG by rapidly measuring intensity in a short strip near the quiet disc centre effectively at every 14 km on the sun; the measurements were digitized and stored on a magnetic tape. They detected the existence of details in the quiet SG up to a wavenumber of $240 \times 10^{-4}\text{km}^{-1}$ *i.e.*, a wavelength of one third of an arcsec. However, they have not indicated the precise methodology by which such a high resolution has been attained. Knox (1975) completed his Ph.D. thesis : Diffraction limited imaging with astronomical telescopes, while Aime & Ricort (1975) gave a statistical analysis of SG.

Kinahan (1976) improved the system used by Harvey & Schwarzschild (1975) by converting one-aperture telescope into a two-aperture telescope, besides other modifications. Aime (1976) showed that except for very good seeing, the signal to noise ratio (S/N) is higher in the speckle techniques than in the Michelson interferometry experiments. Nisenson *et al.* (1976) computationally generated the deblurred images of solar details making use of the image reconstruction algorithm of Knox & Thompson (1974) later known as 'speckle imaging' technique. Labeyrie (1976) reviewed various high resolution techniques employed in optical astronomy. Schneidermann & Karo (1976) reviewed the requirements of subsystems of the general speckle IFM *i.e.* the magnification system, the shutter, the wavelength & bandwidth selector, the sensor and data recording and analysis including a discussion of S/N ratio.

Aime *et al.* (1977) proposed a method for PS (power spectrum) calibration via Michelson stellar interferometry in continuation to Aime's (1976) work, while Aime & Roddier (1977) introduced 'one-dimensional speckle interferometry' as a compromise between the standard speckle interferometry and the Michelson interferometry for precise, high resolution images. Using the latter method, Aime (1977) successfully conducted a statistical analysis of SG and Stachnik *et al.* (1977) reported the first results from speckle image reconstruction of the actual solar features. In continuation to his earlier work, Fried (1966, 1978) determined the probability of getting a lucky short-exposure image through turbulence. Aime *et al.* (1978b) found an exponential decrease of the SG-PS by conducting one-dimensional speckle interferometry which got confirmed again by Aime (1978a, c). Labeyrie (1978) has pointed out several relevant features for designing and fabricating a speckle IFM.

Suggesting a new model for SG, a morphological interpretation of SG-PS was given by Aime (1978b), and Aime *et al.* (1978d) reported the changes in the atmospheric lens MTF for the purpose of calibration. Ricort & Aime (1979) and Aime (1979) could precisely measure the energy spectrum of SG up to 3 cycles per arcsec. Aime *et al.* (1979) conducted a harmonic analysis of the spatial distribution of the centres of gravity of granules and confirmed that SG obeys neither a perfect order (like laminar convection) nor a total disorder (like highly turbulent convection).

Aime & Ricort (1980) made a comparative study of corrected SG-PS by using four different methods of calibration for the effects of atmospheric turbulence. They inferred that a pseudo-convective model should probably be adopted for explaining the origin of SG. Greenaway (1981) derived and compared the isoplanatic patch sizes for speckle interferometry and adaptive optics while Stachnik (1981) threw a new light on solar speckle imaging on the basis of several laboratory experiments. Roddier (1981) reviewed very usefully the effects of atmospheric turbulence in various branches of optical astronomy. Ricort *et al.* (1981) conducted a study of SG under partial eclipse conditions by speckle interferometry and von der Luhe (1981) showed that optical and digital Fourier transformation of SG lead to the same quantitative results, although it was claimed that under suitable conditions, optical Fourier transformation should be a reliable alternative. Kadiri *et al.* (1981) experimentally proved that a considerable gain in contrast is obtained by using rectangular/one-dimensional aperture which can obviously be used for high inensity solar observations. This later lead to the concept of a "Slit Aperture Telescope" *i.e.*, SAT. Aime *et al.* (1981) reported day time measurements of temporal autocorrelation functions of solar speckle patterns done on the McMath solar telescope. In the space of only few minutes, rapid variations of time constants were observed by them.

For some observations, a single and high value T of time constant was obtained, average 170 ms, standard deviation 80ms. The temporal autocorrelation functions were consistant with theoretical curves obtained from a single layer atmospheric turbulence model. For other observations a super-imposed short time-constant τ, showing little variation around 5.5 ms (standard deviation 1 ms) was also present. It was shown that T depends on the diameter of the telescope D and that the value of the short time scale τ when it occurs, is correlated with the Fried parameter r_0 (introduced by Fried 1966).

Bates (1982) reviewed the status of astronomical speckle imaging making only brief comments for solar researches. Petrov *et al.* (1982) showed theoretically as well as experimentally that a cross spectrum analysis in speckle interferometry allows determination of an unbiased estimate of the image Wiener spectrum without changing S/N ratio (where the real part of the cross spectrum is used as an estimate of PS). Durrant & Nesis (1982) studied the small-scale velocity fields in the vertical structure of the solar photosphere while Ricort *et al.* (1982) made a comparison between the estimates of r_0 obtained by measurements of SG contrast and of the variance of angle of arrival fluctuations. Aime *et al.* (1982, 1983) described the schematic design of a domeless, altazimuthal mount low cost SAT of 4 × 80 cm proposed for Nice Observatory. Stachnik *et al.* (1983) used a general electric high-linearity, liquid nitrogen cooled CID (charge-injection device) camera on the McMath telescope for recording accurately the extremely low contrast speckles that occur for the sun. Reconstructed images of sunspot penumbrae and of pores show evidence for details at scales as fine as 0.″11 (80 km), despite prevailing seeing conditions of 1″ to 2″, approaching the diffraction limit of the telescope, (at 410 nm 0.″055 or 40 km). The finest structures (presumably magnetically controlled) appear to be embedded in penumbral filaments, while coarser subarc second detail appears in some, but not all, of the pores studied.

von der Luhe (1984a, b) described a method (the spectral ratio technique) for estimating r_0 from a time series of arbitrarily resolved structures imaged through atmospheric turbulence and Petrov *et al.* (1984) explained almost all the technical design-details with corresponding advantages on undertaking the proposed large slit aperture telescope (LSAT) project for either solar or stellar purposes.

Christou (1985) completed his Ph.D. thesis on seeing effects and their calibration for astronomical speckle interferometry observations. von der Luhe (1985b) carried out his Ph.D. thesis work on speckle image reconstruction of solar small scale structure observations. von der Luhe (1985a) studied the effect of anisoplanatism on high resolution speckle imaging of solar small scale structures and von der Luhe (1985c) studied the speckle masking transfer function, a still refined reconstruction technique. Using again the McMath telescope, Aime *et al.* (1985) reported the preliminary results based on speckle interferometry on the correlation between intensity and velocity in SG. They also suggested the use of CCD-type detectors for significantly improving the S/N

ratio. Mattig (1985) amply reviewed quite a number of observations on the high resolutioin structure of the sun, alongwith related problems.

Roudier & Müller (1986) analysed the structure of SG using computer processed images of two very high resolution (0.″25) white-light pictures obtained at the Pic-du-Midi observatory. They conclude that the granules appear to have a 'critical' or 'dominant' scale/size of 1.″37, at which drastic changes in the properties of granules occur. Roudier (1986) completed his Ph.D. thesis, reporting an increase of the granule number with the solar activity. Aime *et al.* (1986) developed a cross-spectrum analysis technique that makes it possible to compute an unbiased estimate of the speckle pattern Wiener spectrum. Using a one-dimensional IFM, this technique gave results, besides others, on the study of atmospheric MTF, the space-time properties of speckles and the convective motions of solar photospheric microstructures. Their most fruitful result refers to brightness-velocity cross spectrum from speckle spectroscopic experiments.

von der Luhe *et al.* (1987a) discussed the calibration problems in solar speckle interferometry and von der Luhe & Dunn (1987) observed SG with a RCA CCD diode array camera (512 × 403 pixels) at the Sacramento Peak Observatory (SPO) vacuum tower telescope by taking time series of short exposure (4 ms) pictures of a 14″ × 14″ quiet region near the solar centre (consecutive frames separated by 0.55 sec in time). They could recover signals up to a spatial frequency of 2.5 line pairs per arcsec, corresponding to a wavenumber of 22 Mm^{-1} or 40% of the diffraction limit of the telescope under 1.3 arcsec average seeing conditions and estimated a corrected rms SG contrast of 0.127 ± 0.01, besides observing an exponential fall off of the power density towards higher spatial frequencies.

von der Luhe (1987 b) explained the use of KISIP (Kiepenheuer Institute Speckle Imaging Package) as a very useful tool for high resolution solar imaging, having combined the Fourier amplitude recovery of Labeyrie (1970) and Knox & Thompson (1974) phase recovery techniques. von der Luhe (1987c) described the use of speckle imaging techniques for the study of sizes, brightness and dynamics of solar facular points. He made use of two 35 mm film cameras and an RCA 501 'thinned' 512 × 360 pixel CCD to record data with the SPO telescope, an area 128 × 128 pixels (5.5 × 5.5 arcsec) was actually recorded.

The immediate and long term scientific goals for solar interferometry were lucidly laid down by von der Luhe & Zirker (1988) while von der Luhe (1988) investigated the signal transfer function of Knox-Thompson speckle imaging technique, also applicable to extended objects including the sun. Roddier (1988) has given a complete and concise developmental status of the science of interferometric imaging in optical astronomy wherein the important results and potential with reference to solar speckle interferometry have been enumerated. Pehlemann & von der Luhe (1989) discussed technical problems arising during the implementation of a 4-dimensional speckle masking algorithm to reconstruct diffration limited 2-dimensional images of extended objects; in particular, they presented sample reconstructions of a section of the solar photosphere *i.e.*, a set of 100 speckle frames of a 5.″2 × 5.″2 field (128 × 128 pixel) was taken with the 76 cm vacuum tower telescope at SPO. A bandpass of 50 Å width was centred at 5850 Å, and the frames were taken every 0.6 sec with an exposure of 4 ms. These resulted in an estimation of r_0 equal to 13.3 cm, which is rather good for day-time seeing. Hogbom (1989) described a method for reconstruction from the focal volume information. Druesne *et al.* (1989) have reported a study of the centre-to-limb variation of SG-PS with speckle interferometric technique at the McMath telescope. They took one-dimensional photoelectric scans of the solar surface after diaphragming the telescope into a SAT of 152 × 3.2 cm to eliminate foreshortening problem and obtained PS up to 2 arcsec (angular frequency) free of photon noise bias, using cross-spectrum technique for data processing. For angular frequencies higher than 0.4 arcsec, the power spectra are well approximated by exponentially decreasing curves that indicate a fall of power in the highest frequencies towards the limb and the rms contrast of the solar granulation displays a monotonic centre-to-limb decrease. The authors have also attempted to interpret these results morphologically, concluding that (i) smaller granules are probably detected under the quiet sun conditions, (ii) a variation of SG-PS may occur with the solar cycle and, above all, that (iii) the centre-to-limb decrease in the rms contrast of SG is essentially due to a loss of power in high angular frequencies. Druesne (private communication 1990) suggests the use of a CCD detector instead.

Engvold (1990) has reviewed the new observational aspects of speckle imaging vis-a-vis large solar telescope projects underway. Rodriguez Hidalgo *et al.* (1990) have derived r_0 from the observations of SG outside the disc centre. Roudier *et al.* (1991) have given statistical analysis of the granulation velocity fields provided by the Multi-channel Subtractive Double Pass (MSDP) spectrograph of Pic du Midi Observatory.

3. Solar granulation

It is well knwon that the sun is a dwarf star of spectral class G2, a typical member of the lower main sequence of the H-R diagram and it is the only star on which we are ever likely to observe the resolved granules (when examined with a reasonably powerful telescope under good seeing, the sun's surface exhibits a fine structure comprised of an irregular cellular pattern of polygonal bright elements, known as granules, separated by narrow dark lanes). Over the whole surface of the sun, there are about four million granules with an average diameter 1.3 to 1.4 of arcsecond, corresponding to 1000 km in size.

As shown convincingly since 1957 by modern observations, SG is basically a convective phenomenon, each granule and its surrounding dark material representing one convection cell. These granules are actually visible manifestations of sub-photospheric convection currents that are largely responsible for the outward transport of energy from deeper layers and hence help in maintaining the energy-balance of the sun as a whole.

The visibility of SG decreases as one goes from the centre towards the limb and finally it stops altogether. Schmidt *et al.* (1979) found the granular brightness contrast to decrease monotonically towards the limb; at $\cos\theta = 0.2$, the magnitude of the contrast is about 3 times smaller than at the disc centre. Now, an estimate of the distance from the limb at which the granules disappear gives an indication of the height up to which the granules extend into the upper atmosphere. It has already been proved that SG exist in radiation arising nominally at a height of 100 km or more and that the granules are visible up to 5 arcsec from the limb, corresponding heliocentric angle being 84° and nominal optical depth equal to 0.1 (*i.e.* cos 84).

Observations of the SG lie at the limit of those technically feasible with both ground based- and balloon-borne telescopes, because a sub arcsec spatial resolution is quite hard to achieve. Balloon-borne telescopes are too small and ground based telescopes suffer from seeing limitations. Since the wavefront distortion is continuously changing, the number and locations of diffraction images change as well, but this pattern gets effectively frozen, if the exposure time is short compared to the time scale of atmospherically induced fluctuations. In that case, the individual diffraction images (or speckles) are not degraded and the reconstruction of such diffraction limited images of point sources using these speckles has quite rapidly developed as a high resolution technique in astronomy. The performance of interferometric methods can be improved by increasing the number of pictures averaged, achieved by increasing the frame rate necessitated by the time constraints imposed by the life time of the structures. The best one could hope for, as suggested by von der Luhe & Zirker (1988), are video rates, about 30 frames per second. About 1000 frames i.e., 30s in time can thus be combined to a single reconstructed picture. In spite of highly developed video technology, the data handling and data reduction problems have to be solved by using high speed computers, besides development of fast algorithms.

Image-motion and image-distortion together constitute the astronomical seeing and one has to take account of these factors while deciding upon the mode of observations and analysis procedure, besides the telescope aperture.

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