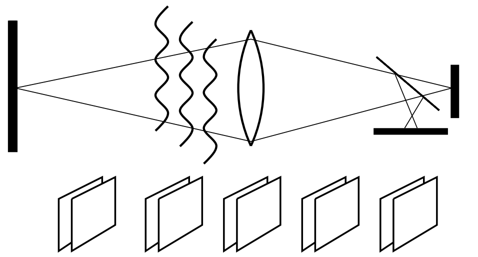
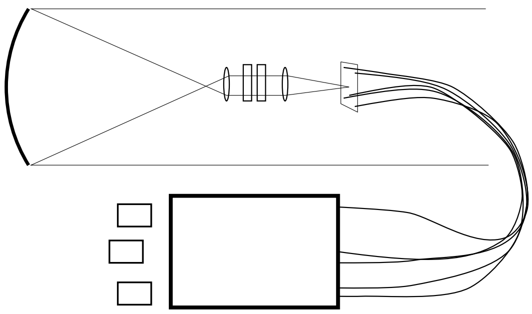
DOT SPECKLE SPECTROMETRY

Application for NFRA support





Summary

This application concerns the development of phase-diverse speckle imaging and spectrometry for the Dutch Open Telescope (DOT) on La Palma. The DOT is — finally — becoming operational. Its open principle represents a major new approach in optical solar physics. If it performs to expectation, the DOT will provide angular resolution at the limit set by the La Palma seeing. This proposal outlines schemes to beat the latter, utilizing phase-diverse speckle reconstruction in two projects:

- development of production-line phase-diverse speckle image restoration;
- development of phase-diverse speckle Stokes spectrometry.

These projects form a natural sequence. The first will turn the DOT into the prime high-resolution imager for science in conjunction with the SOHO mission. The second exploits unique DOT capabilities in an instrument that may be seen as the ultimate photon-processing machine in optical solar physics. It will make the DOT surpass all other solar telescopes in high-resolution high-precision 2D multi-line Stokes spectrometry, precisely what is needed in studies of solar magnetism.

This initial proposal summarizes the science interest in such capability and outlines the schemes. These are ambitious projects that exceed Utrecht capabilities, fit well within current and desirable NFRA expertise, and have strong links to developments in nighttime astronomy.

Contents

1 Introduction

The Dutch Open Telescope (DOT) was envisioned long ago by C. Zwaan as a facility to map and understand solar magnetism. This research topic remains its highest priority. Even though the development of the DOT has been overly long, the telescope yet promises capability for a major role in this field. The image restoration schemes proposed here will make it a unique facility. My claim is even stronger: if they can be made to work, they are likely to revamp the field completely.

This is an initial proposal, conforming to the guidelines in the announcement of opportunity. I summarize the science context in the next section and I describe the DOT in some detail to provide background. Phase-diverse speckle imaging and phase-diverse speckle spectrometry are outlined rather briefly by giving their principles rather than detailed work plans. The latter require expert feasibility study that I hope to initialize with this proposal.

2 Solar surface magnetometry

Solar magnetism. Magnetism lies at the root of most solar and heliospheric physics. The intricate structure of the solar field, the activity cycle and the influence of the field on the heliosphere represent major quests of (astro-)physics which bear directly on the human environment. The sun's magnetic field is generated by enigmatic dynamo processes in the solar interior, is organised into the highly complex patterns of solar activity observed in the solar photosphere, dominates the structure of the outer solar atmosphere (chromosphere, transition region, corona), regulates the solar wind, and affects the whole extended heliosphere.

The DOT aims at studies of the magnetic field structure and dynamics in the solar photosphere and chromosphere. In this regime, the plasma β parameter (ratio of gas to magnetic pressure) flips from large to small across unity, so that the field role switches from being dominated by gas motions to dominating gas motions. At the solar surface, the field displays patterning imposed by the subsurface dynamo and convective flows while, at the same time, it controls flows and wave motions to the outer atmosphere. Solar surface magnetometry aims to understand the fundamental how and why of the field topology and dynamics (cf. Rutten and Schrijver 1994).

Topology. Solar surface magnetism consists of a remarkable hierarchy of discrete strong-field structures (Zwaan 1987). The basic entity is the flux tube. Solar flux tubes have tiny cross-sections (0.1–0.2$''$) but have become observable with the Canary Island telescopes nevertheless (Fig. 1, top left). The flux tubes are arranged into a coarse network pattern regulated by surface flows, and occur in larger density in solar plage (faculae). The flows are imposed by the turbulent convection of which the granulation pancake pattern is the most evident characteristic. The solar granulation is now understood through numerical simulation, but the dynamical interaction between convection and flux tubes remains a topic of large interest. The same holds for the larger elements in the magnetic hierarchy, pores, umbrae, large spots with penumbrae, and fully-developed active regions. Current results on spot topology indicate the presence of much shear between horizontally and upwards directed penumbral field bundles (Fig. 1, bottom left), while the nature and cause of umbral fine structure has not been identified. Active regions possess complex topology and rich dynamics at their emergence (Fig. 1, right) that requires mapping with high-resolution Stokes vector magnetometry. The same holds for their subsequent decay.

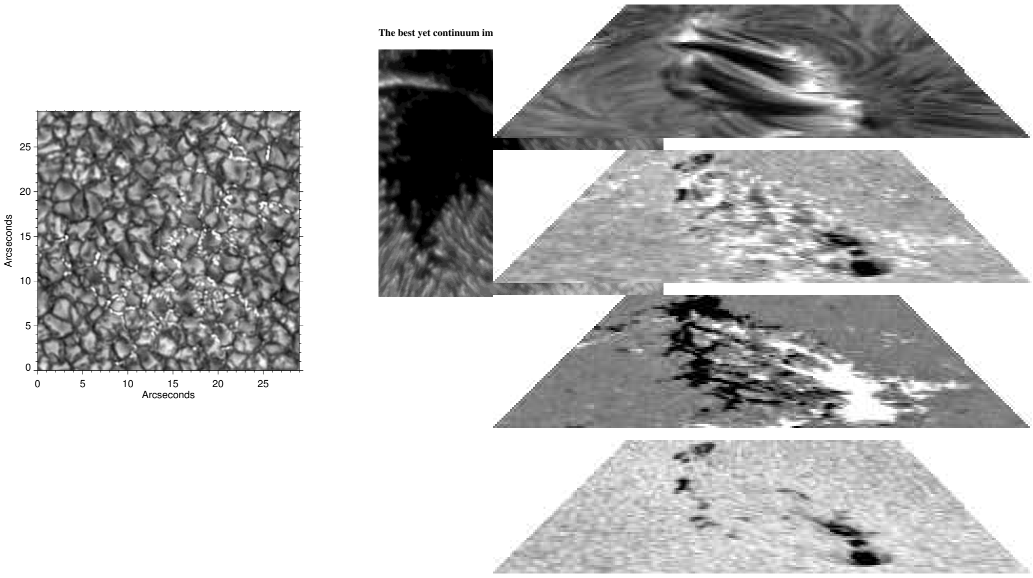


Figure 1: Overview of solar magnetic structures. Images taken with the Swedish Vacuum Solar Telescope (SVST) on La Palma. • Top left: high-resolution G–band image of the photospheric granulation (Lockheed). Scale: 22 Mm (30″) to a side. This image has been restored for atmospheric wavefront deformation through phase-diverse speckle reconstruction. The resolution reaches the telescope diffraction limit of 0.2″. The tiny bright points in the dark intergranular lanes mark strong-field (150 mT) flux tubes. The Fraunhofer G band (around 430.5 nm) displays these features with extraordinary contrast. • Bottom left: high-resolution image of a sunspot penumbra (Lockheed). Scale: 35 Mm (50″) to a side. The filamentary structures mark complex topology consisting of horizontally as well as upwards tilted fans of field bundles. One bundle arches over the umbra. • Right: tomography of an emerging active region (Strous 1994). Pseudo-perspective projection of a photospheric image (bottom, continuum near $\lambda = 557$ nm), the photospheric magnetic field measured from Fe I 630.2 nm, the intensity at the center of this line, and the chromospheric topology displayed by Hα 656.3 nm (top). Scale: 54 Mm (75″) to a side.

Dynamics of magnetic structures. The paradigm of stellar activity says that stellar coronas and chromospheres are heated magnetically (Schrijver 1995). Since the fields are anchored in the dense gas at the surface, the dynamics of flux tubes, pores and spots lie at the root of outer-atmosphere heating. Thus, a fundamental goal in solar magnetism research is to measure the motions that convection imposes on the magnetic elements and to find how these control the dynamics in of the outer atmosphere. By combining high-resolution surface magnetometry (DOT) with ultraviolet spectrometry and imaging of the chromosphere (SOHO), we may correlate and trace surface motions and corresponding chromospheric dynamics in magnetic structures tomographically all the way out into the optically-thin plasma regime (cf. Cook *et al.* 1996, Hoekzema *et al.* 1997).

Patterns of solar activity. The emergence and disappearance patterns of magnetic flux on the solar surface betray the workings of the solar dynamo (*e.g.,* Balke *et al.* 1993, Strous *et al.* 1996).

Active regions consist of emerging bundles of loops that drain through convective collapse (right-hand part of Fig. 1). The nearly E–W orientation of the great majority of bipolar active regions together with Hale's polarity laws indicate that Ω-shaped loops emerge from toroidal flux ropes which probably originate in an overshoot shell underneath the solar convection zone. Currently, helioseismology boosts global dynamo insight by mapping subsurface flows and temperature gradients. Solar surface studies should establish the required upper boundary constraints to the dynamo by identifying the processes and topology of flux emergence and disappearance at the fundamental level of individual flux tubes. This is now in reach through combining high-resolution groundbased magnetometry with the continuous low-resolution magnetometry provided by SOHO (SOI/MDI). The Utrecht group is closely involved with the larger-scale SOI/MDI analyses headed by C.J. Schrijver at Lockheed (Palo Alto), currently through Mandy Hagenaar (AIO). The next step is to add higher-resolution groundbased sequences that resolve and track individual flux tubes — both in quiet areas (network fields) and, with mounting solar activity, for active regions.

High resolution prospects. High angular resolution is the science driver for the DOT (and for all other solar telescopes excepting helioseismology). As detailed below, the DOT aim is to furnish image quality that is set by the non-local seeing alone, not by the telescope or by local disturbances caused by the telescope or the support structure. The next quest is to minimize the wavefront perturbations caused by the non-local seeing. Even at La Palma "super-seeing" is rare. Even the Swedish Vacuum Solar Telescope (SVST), which provides the sharpest images worldwide, does not often reach image quality better than $0.5''$ resolution. Taking the long-duration sequences of the quality that is needed to localize and track individual flux tubes (as in the upper-left image in Fig. 1) requires seeing that may occur only once or twice a year. The new technique of phase-diverse speckle restoration therefore promises a dramatic improvement by providing super-seeing resolution when the seeing is only fair to good. It actually reaches the diffraction limit of the telescope in the latter case. Such resolution increase represents a true breakthrough. By going from $1''$ to $0.2''$ resolution we reach the basic limits of scale heights and photon free paths (50–100 km; $1''$ corresponds to 725 km) that also regulate flux tube diameters. Getting this high resolution at long duration enables us not only to glimpse flux tubes, but to track them and so study the solar dynamo patterning in its fundamental representation.

Timing. Even though the DOT development has been excessively long, its completion and the projects described below have excellent timing. The open principle and the basic design of the DOT remain, when verified, uniquely suited to high-resolution studies. Realization of phase-diverse speckle restoration may now increase the hit rate of diffraction-limited resolution by a large factor. The required hardware and software technology developments are in reach just now. The above research will be done in close relation to SOHO data gathering; SOHO's guaranteed support was recently extended by five more years (by ESA, but NASA will undoubtedly follow). Solar activity, presently at minimum, cooperates over the coming years by increasingly providing targets of opportunity. All these factors, plus the NFRA's own timelines, suggest a five-year plan starting mid-1998 after the DOT verification, with some initial feasibility studies starting the coming winter.

3 Dutch Open Telescope

DOT principle. The DOT structure is novel to astronomy. The telescope and the support tower are both open and there is no dome, only a fold-away bad-weather canopy. At La Palma, the best daytime seeing tends to occur when strong winds from Northern directions suppress the convective plumes that arise from local ground heating. The DOT's principle is to minimize obstruction to the local air flow and to rely on the same winds, blowing right through the telescope, to inhibit convective turbulence within the telescope and in its immediate surroundings.

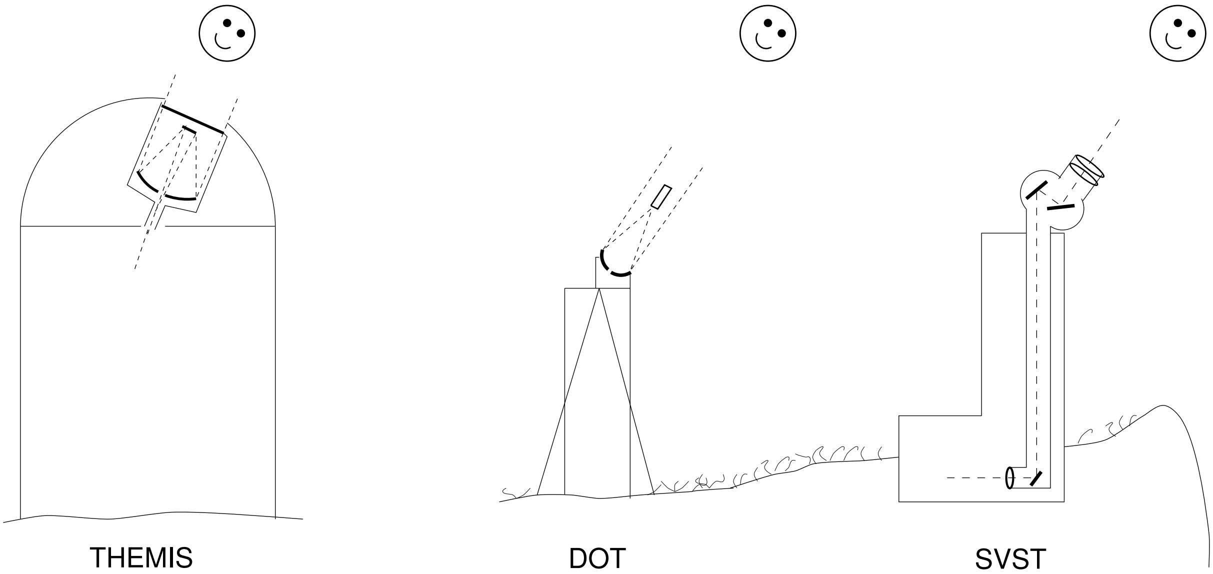


Figure 2: Solar telescope principles: THEMIS, DOT and SVST. Apertures and telescope heights above ground about to scale; telescopes, buildings and mountains not to scale. THEMIS is an alt-az vacuum reflector with highly complex postfocus instrumentation. The latter fills the whole building. The DOT is an open reflector. The SVST is a vacuum refractor with an alt-az heliostat. The DOT is located 60 m downslope from the SVST, somewhat further from the exceedingly steep Caldeira slope which acts as a chimney in the daytime. The best seeing occurs at strong trade winds (5–10 m/s) from the North, here to the left (without wind, the line of sight to the sun crosses the Caldeira plume. Note that the La Palma broom helps by reducing ground heating.) The DOT and the SVST share utmost optical simplicity and possess superb imaging elements. In contrast, THEMIS has 6 curved reflections before its main focus (plus 5 flat mirrors plus the vacuum window). Its main mirror was flawed and is being replaced. The DOT is operated from the SVST building, making it easy to use the two telescopes in tandem.

The open design of the DOT departs radically from existing solar telescopes (Fig. 2). All current high-resolution telescopes rely on internal evacuation to avoid internal turbulence. For these, the vacuum window (in reflectors such as the NSO 76 cm VTT at Sacramento Peak, the German 70 cm VTT at Tenerife, and the French-Italian 90 cm THEMIS at Tenerife) or the objective lens (in refractors as the Swedish 47 cm SVST on La Palma) set a restrictive size limit. Thus, the DOT represents an important test for large-telescope concepts. If the open principle works satisfactorily, it may be the way to grow. Also for the DOT itself. The current DOT aperture is 45 cm, but the mechanical structure accepts an 76 cm mirror without change and a yet larger one with only minor modification.

DOT design. The DOT is a reflector with a parabolic mirror that sits out in the open at a height of 15 m. The mirror (currently Cervit, 45 cm diameter, focal length 200 cm, peak-to-peak surface quality better than $\lambda/10$, rms better than $\lambda/50$) focuses the incoming beam onto a water-cooled diaphragm that reflects most of the image out of the telescope and transmits only a 2×2 arcmin subfield. Initially, the latter will be recorded with a video CCD through a 1 nm G-band ($\lambda = 430.5$ nm) filter using relay optics including a microscope objective to obtain pixels of $0.1''$. The video signal is transported per optical link to the SVST building where the DOT enjoys generous hospitality.

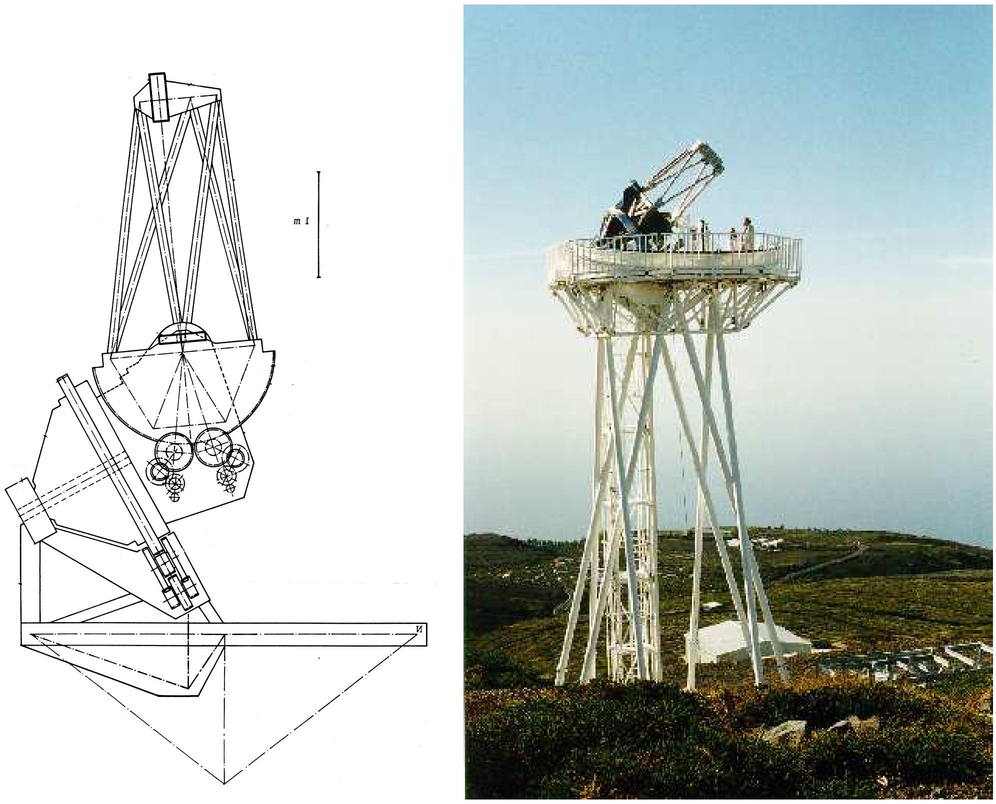


Figure 3: Left: sketch of the DOT pointing at the sun from La Palma at noon on June 21. The bar measures 1 m. Right: The DOT on its tower, La Palma, October 1996. North is to the right. The building of the Carlsberg transit telescope, HEGRA and the Residencia are seen in the background.

The mirror is mounted deformation-free with nine-point axial and three-point radial support in a parallactic telescope structure that is considerably overdimensioned as well as unbalanced in order to obtain extreme pointing stability at very low dissipation. The latter amounts to only about 20 W, three orders of magnitude less than the heat production of the oil bearings in the nearby WHT. Brushless pairs of servo motors in push-pull preload configuration without backlash drive 4-step gear trains achieving 1:75,000 reduction with self-aligning gears.

The 15 m high support tower, at 13 tons considerably lighter than the telescope itself, permits only lateral motion of the platform. It consists of open steel-tube triangles and is designed to withstand large ice loads and wind pressure — the ladder and elevator cage may fill up with 30 tons of ice.

The bad-weather enclosure opens clam-like and folds away to the sides. It is made of heavy polyester fabric mounted on steel ribs and may be closed in winds up to 30 m/s (or opened, but that is less likely). When closed it should withstand the 70 m/s (Bf 12) winds that might hit Roque de los Muchachos.

DOT status. The tower, platform, telescope and enclosure have been mounted on the La Palma site during the past summer. The telescope drives and drive controls (located in the SVST building) function properly. The optics have been mounted in a full-size interferometer at Utrecht over the past weeks in order to construct a precise major-axis and focus defining laser system that guarantees high-precision alignment at all times. This is now complete and the mirror will soon go to La Palma; first light and first images are expected during summer.

Air-suction experiments, near the prime-focus diaphragm and elsewhere within the open telescope structure and combined with schlieren diagnostics, will follow in order to optimize the internal heat budget. These experiments will be time consuming but are essential to obtain diffraction-limited performance of the telescope itself as frequently as possible.

The final verification test of the open principle will consist of real-time image quality comparison with the SVST. The telescopes are similar in having a 45–47 cm aperture and in offering their imaging element as first piece of optics to incoming solar photons. In the case of the SVST, that is the doublet lens; in the DOT, the parabolic mirror. Thus, the two telescopes represent basic extremes of the refractor and reflector concepts, respectively. It is exciting to compare these at one site.

STW funds the DOT installation and verification for technological reasons. From the solar physics point of view, the verification concerns the open principle. From STW's technological point of view, the verification concerns the stiffness and pointing stability of the telescope, the drives and the support structure. Future DOT funding must obviously be science-oriented.

DOT timing. Let me add two personal comments on the excessively long DOT development time. The first is that this long duration obviously has to do with the fact that this project has been a one-man show over two decades. The manpower funding from STW over the past years has accelerated its progress. The long duration has obviously also to do with Hammerschlag's rigorous finickiness. His emphasis is on utter precision without any sacrifice whatsoever for expediency. This choice is debatable (and is debated) in many instances, but it is true that in my experience no other solar telescope than the SVST produces its intended resolution — something or other (dome, vacuum window, alignment, windshake) spoils the show. The SVST has limitations due to its being an alt-az refractor that the DOT does not have (aperture limit, large instrumental polarization, image rotation, large daily focus shift, large focus change with wavelength) and which inhibit multi-line Stokes spectrometry as outlined below. The DOT may well turn out to be world-class competitive thanks to its painstakingly slow development.

Second, the DOT is now much better suited to tackle high-resolution studies than when C. Zwaan originally suggested these. He was thinking in terms of ciné film registration with subsequent microdensitometering and computer processing. Even the latter would have been too costly for university departments when only few institutions possessed imaging machinery. This has radically changed with the advent of CCD cameras, workstations, gigabyte disks and IDL. Image processing is now done at Utrecht with the same sophistication as at Lockheed, as shown in the thesis of Strous (1994) and the upcoming theses of Hoekzema (December 1) and Hagenaar (1999). Even a small university group may now comfortably operate gigabyte data acquisition and processing at the solar physics high-resolution frontier. This is vividly demonstrated by the highly successful Stockholm group running the SVST. It currently consists of Prof. G. Scharmer, Dr. D. Kiselman, PhD student Rouppe van der Voort (a recent Utrecht graduate) and another PhD slot, no more.

DOT plans. Let me briefly summarize the current plans for science with the DOT. Obviously, these assume that the telescope will pass its verification tests. In the spirit of the comments above, I have high expectation that it will perform to specification. Equally obvious, these plans require funding not part of the present proposal.

The initial DOT post-focus equipment is in principle limited to verification imaging (since funded by STW), but it can in practice used already for science, especially in tandem with SVST observing (such two-telescope usage has for example been requested by a CFA–IAC team). In addition, other simple equipment may be borrowed from the SVST.

Currently, there are three postfocus instrumentation plans, each involving an optics package provided by another group:

- Lockheed tunable filter (SOUP). This is a versatile tunable birefringent filter that was developed — at large cost — for use in space and that has flown on the Spacelab 2 mission (Title *et al.* 1989). We have been offered the loan of the SOUP for use at the DOT. Its size requires location behind the main mirror. The polarization information is best encoded just after prime focus, before the reflections that bring the beam through the mirror hole. The new developments in liquid-crystal retarders (MeadowLark Optics) make liquid-crystal encoding the best option. Combining this with the SOUP produces instrumentation comparable to what is currently used at the SVST.
- Italian magneto-optical filter (MOF). So-called Cacciani magneto-optical filters are primarily used in helioseismology (Tomczyk *et al.* 1995) but may also be adapted for high-resolution magnetometry (Cacciani *et al.* 1990). The major advantage of a MOF for the DOT is its comapctness. It can easily be mounted besides the incoming beam and possibly even behind prime focus. Realization of a DOT MOF is being sought in collaboration with the solar physics group at Naples.
- Canadian H-alpha filter. A third filter possibility is to refurbish and install a high-quality H-alpha Lyot filter donated to the DOT by the Canadian Research Council. It was used for many years at the Ottawa River Solar Observatory until its closure. H-alpha does not provide direct magnetic field measurements, but images taken in this line do show the topology of chromospheric fields in the form of fibrils. This filter may also be mounted behind the mirror.

Another option that is being discussed with a group at the Berlin DLR (Deutsche Luft- und Raumfahrt) is to replace the current DOT mirror with a 76 cm one at their cost. It will enable daytime solar physics with the present prime-focus structure and nighttime asteroid astrometry in a Nasmyth focus. The DLR group is motivated by the extreme pointing precision of the DOT.

4 Phase-diverse speckle image restoration

Introduction. The first project of this proposal is to develop phase-diverse speckle interferometry into a large-volume imaging machine. The basic technique has been demonstrated and is highly promising. What is needed is development from demonstration to regular daily application. This requires expertise and efforts in fast processing, possibly hardware, certainly software. Developing such techniques has direct links to adaptive-optics and post-detection restoration techniques in nighttime astronomy.

Technique. The basic idea of solar image restoration is to use the granulation of the solar surface as an encoder of speckle information to achieve interferometric image reconstructions. This may be done on the granulation images themselves, but may also be extended to concurrent narrow-channel restoration (Keller and von der Lühe 1992). The scheme is extended to Stokes spectrometry in Section 5 below. Its broad applicability derives from the ubiquity of granulation over the solar surface and throughout the optical spectrum. Granules are not point sources and they are not bright (low contrast), but they do provide spatial wavenumber encoding over every isoplanatic patch on or above the solar surface (except in active regions, but these abound in suitable fine structure of their own).

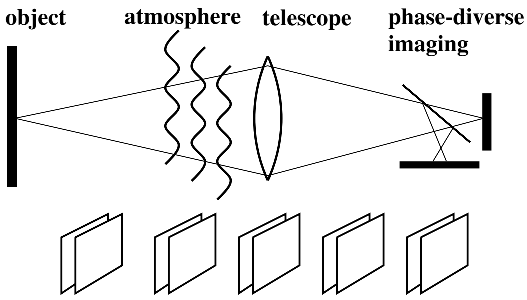


Figure 4: Phase-diverse speckle image registration. Following an idea originally due to Högbom (in Rutten and Severino 1989), synchronized short-duration (about 10 msec) pairs of granulation exposures are registered both in focus and out of focus. Five pairs suffice to produce reliable restoration of the wavefront to the telescope diffraction limit when the seeing is reasonable.

Recently, solar speckle reconstruction methods have been combined with phase-diverse registration in an important development by Löfdahl and Scharmer (1994) and Seldin and Paxman (1994), culminating in the landmark paper of Paxman *et al.* (1996). The principle is shown in Fig. 4. In principle, one should sample the full "focal volume" (Högbom); in practice, one frame in focus and one simultaneous frame out of focus delivers reasonable restoration; five such phase-diverse pairs taken within the time over which the solar granulation does not change (about 20 s) produces fully reliable restoration up to a dozen or so Zernike terms. The advantage of this technique is that far fewer frames are required than in pure speckle interferometry. The latter typically requires about a hundred samplings of atmospheric wavefront deformations within the time in which the object pattern is constant. Phase-diverse registration limits the required frame rate by an order of magnitude.

The resolution increase of up to a factor five represents improvement comparable to what will be reached by future adaptive optics. The method can be seen as adaptive optics *a posteriori*, or even as multi-conjugate adaptive optics (Beckers 1989) *a posteriori* because there is no field limitation. Tesselation may be used to cover a wider field than the single isoplanatic patch that adaptive optics can handle. The cost of the method is the large amount of post-detection computer processing.

Project: from demonstration to production. At the moment. phase-diverse speckle restoration has been demonstrated convincingly by Paxman *et al.* (1996), but it is yet far from a robust routine data production. What does it need? Optically, phase-diverse registration is simply achieved with a phase-delay beam splitter that puts an in-focus and an out-focus frame next to each other on one chip, so that exact exposure synchronization is guaranteed. CCD readout of five 10 ms exposures within a few seconds at low readout noise becomes feasible with off-the-shelf technology. Thus, the hardware requirements need attention but are no show stoppers.

The problem sits in the processing. Sofar, the demonstrations have been limited to small-field short-duration sequences, taking days or even weeks of computer time for the subsequent restoration. The issue is whether the processing may be speeded up sufficiently that it may keep up with data taking over larger fields and longer duration. If overnight processing does the job, phase-diverse speckle imaging becomes a fantastic production machine. My proposal is to find out whether this is feasible and to get such a machine working at the DOT if it is feasible.

First applications: G and K imaging. An immediate application of such large-volume restoration is to use it on G-band imagery in order to produce sequences of the quality shown by the processed frame at the upper-left in Fig. 1. The white dots mark solar flux tubes. Long sequences of this sharpness would provide precisely the input for the solar physics programs described above. We don't know why the CH lines in the G band show flux tubes so well, but they make an outstanding diagnostic that may be used as proxy magnetometer to map solar magnetism at its intrinsic resolution (Title and Berger 1996, Berger and Title 1996, Berger *et al.* 1995). Long sharp sequences with this diagnostic will provide many SOHO science programs with the basic foot-point constraints set by the field topology in the photosphere.

Second, it will be relatively easy and highly interesting to add a synchronized beam imaging the same field through a 0.1–0.3 nm Ca II K filter. That adds the chromospheric fine structure, including the zoo of chromospheric wave modes that currently attract much attention (reviews by Rutten and Uitenbroek 1991, Rutten 1994, 1995, 1996). In terms of magnetometry, K images show the chromospheric network which is an excellent proxy for the magnetic network (also for reasons yet unknown). Thus, combining speckle-restored G and K filtergram sequences gives the DOT indirect high-resolution magnetometry capability for both the photosphere and the overlying chromosphere.

5 Phase-diverse speckle Stokes spectrometry

Introduction. Let me first clarify the claim that a phase-diverse speckle Stokes spectrometer may be the fundamentally best way to use solar photons in groundbased observing. The intrinsically intricate structuring of the solar atmosphere and its rapid changes require 2D field registration. On the other hand, precise Doppler mapping and magnetometry require spectral resolution of narrow bands within spectral lines. As a result, solar observing strategies have concentrated on filter instruments emphasizing surface patterning at the cost of measurement precision, and on spectrographs emphasizing quantitative measurement at the cost of 2D coverage.

The filter instruments are exemplified by the Lockheed SOUP instrument (*e.g.,* Keller *et al.* 1990, Schrijver *et al.* 1992, Shine *et al.* 1994). The best example of precise spectrometry is the Advanced Stokes Polarimeter (HAO, at the NSP/Sacramento Peak telescope) which is currently the most accurate and productive magnetograph (*e.g.,* Lites *et al.* 1994, Lites *et al.* 1996). It uses detailed profile information of 3 to 5 spectral lines with different Landé factors simultaneously. The French-Italian THEMIS telescope on Tenerife aims to perfect this technique using yet more lines.

Spectrographs offer additional advantage in the form of height tomography through their multi-line capability. For example, a famous échelle setup of J.M. Beckers at Sacramento Peak put Ca II H & K, Na I D_1, Hα and the Ca II infrared lines next to each other on a single detector (70 mm film at the time), spanning most of the solar atmosphere. Most Fourier studies of solar atmosphere dynamics rely on such height-resolved spectrometry (*e.g.,* Lites *et al.* 1993). Multi-line filter observations require multiple beams or sequential observing, both cumbersome, and tend to be limited to a small choice of wavelengths even then.

The coming revolution promised by phase-diverse speckle restoration applies only to 2D imaging because it requires 2D wavefront sampling within the speckle freezing time of about 10 ms. Ideally, such 2D restoration is combined with precise Stokes magnetometry and with atmospheric tomography as achieved in spectrometers. How?

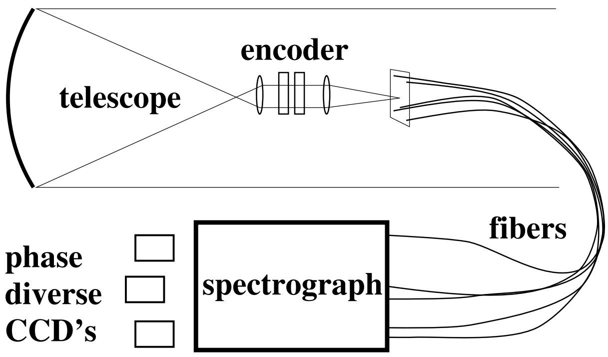


Figure 5: Schematic of a phase-diverse speckle Stokes spectrometer. The DOT input beam is refocused though Stokes encoding optics (liquid crystal retarders) onto a square fiber entrance plate. The fibers are rearranged (not necessarily in any order) into 1D slit coverage, so that the spectrum has the spatial information of the input field transverse to the dispersion. The CCD cameras register selected spectral lines. Phase diversity may be obtained through beam splitters or, as indicated here, by putting one additonal camera out of focus. The scheme permits 2D spectral analysis including Stokes vector measurement at the diffraction limit of the telescope.

Fiber reformatter. The proposed scheme is simple: use optical fibers to reformat a square entrance field into a linear slit (Fig. 5). It resembles the multi-fiber spectrograph inputs used in nighttime applications. The basic idea is the same, but the implementation is quite different. In this case, the fibers have to sample image elements at the diffraction limit of a short-focus telescope, geometrically much smaller than the seeing disks at large telescopes. This characteristic requires thin fibers, only 5 to 10 micron in diameter, which seems to be at the edge of fiber technology — if not beyond it. Hence the need for feasibility study.

The advantages of the scheme are:

- all 2D spatial elements are measured simultaneously;
- full profile information for all measured lines;
- multi-line capability throughout the spectrum;
- phase-diverse image reconstruction feasible per wavelength;
- Stokes vector polarimetry feasible;
- physical separation between telescope and spectrometer feasible.

The disadvantages are:

- small field;
- matching problems.

For example, if 2K chips are used at $0.1''$ pixel size, the field measures only $4.5'' \times 4.5''$. This is much smaller than is typically used in solar imaging, but it covers about one isoplanatic patch which simplifies the restoration processing. And since the data cube of wavelength-resolved restored images is sharp to the diffraction limit, there is time to map other areas before the sun has intrinsically changed.

The matching problems cause the need for small-diameter fibers. Image pixel magnification to coarser fibers won't work because fibers do not conserve solid angle.

The image restoration may employ the multi-channel technique pioneered by Keller and von der Lühe (1992). The continuum windows between the lines are then added up in order to obtain the S/N per frame that is needed for reconstruction. Phase diversity may be obtained through beam splitters or by simply placing one continuum-measuring chip out of focus. The spectrally resolved channels in the spectral lines have far too low S/N per 10 ms frame for direct restoration, but they may be reconstructed in a deconvolution procedure with the restoration matrix from the broadband signal. Addition then yields the required S/N for spectral analysis.

The concept may include Stokes analysis by using liquid-crystal encoders behind prime focus. To first order, seeing does not affect the polarisation measurements if each is restored to the diffraction limit. Of course, this is only the case if the seeing is fair to good — one still needs an excellent site and and excellent telescope or there is no granulation to begin with.

On the DOT. The DOT is particularly suited for such a spectrometer. First of all, it provides the required angular resolution. Second, because it is a reflector rather than a refractor, the focus is co-spatial at all wavelengths (the SVST can only focus a limited wavelength range on its spectrometer slit). Third, the absence of large-angle reflections, of varying reflection angles and of image rotation make it suited to high-precision polarimetry. Finally, the projected aperture increase to 76 cm will give it high sensitivity even in polarimetry.

Proposal. My suggestion is to set up a feasibility study of this concept. If it can be made to work it seems to provide the intrinsically best way to use solar photons in groundbased instrumentation.

Such a study of high-resolution fiber reformatting is also of interest in wider context. For example, J.W. Pel has pointed out that the problem of pushing the 2D fringe pattern at the VLTI combination plane through a spectrometer is very similar.

6 Schematic management and financing plan

The present proposal is an initial one as defined in the announcement of opportunity. It presents the science case and outlines of the projects, but no detailed planning as yet. Indeed, the management plan must be developed, the sources of financing and manpower identified, and technical assessment organised. This is precisely the initial assistance that I am applying for.

Timing. On the DOT side, the verification tests come first. On the NFRA side, the Westerbork upgrade. Thus, a start sometime next year is logical, with initial feasibility orientation the coming winter.

Staffing. The Utrecht staff contribution consists of Hammerschlag and the proposer, both full-time involved in the DOT project apart from their teaching duties – at 20% of the Utrecht staff a considerable investment. In addition, technician Hoogendoorn works full-time on the DOT project; systems programmer van der Zalm part of his time, and much ASTRON-oriented IGF time is spent on the DOT. The STW funding for Bettonvil continues until next summer.

Science support. Utrecht solar physics is not limited to the DOT. Currently, Prof. J.M.E. Kuijpers, hoogleraar B Prof. M. Kuperus and postdoc G.H.J. van den Oord are active in this field. Three theses this year are partially (Tziotziou) or 100% (Schutgens, Hoekzema) devoted to solar physics. Bijzonder hoogleraar Prof. J.P. Goedbloed has turned his Rijnhuizen plasma physics group to solar physics. Emeritus hoogleraar B Prof. C. Zwaan remains very active. At SRON, P. Hoyng is a leading expert in dynamo theory and has interest in helioseismology.

Management. I am obviously willing to be PI of these projects. My motivation is science driven, as befits the role.

National partners. The Utrecht IGF (faculty instrumentation group) and the Utrecht department of computational physics have expressed interest in these projects. The latter group is specialist in high-throughput real-time processing problems. Other groups (such as Hoekstra's TPD department at Delft) are likely prospects.

International partners. Close collaboration with the SVST team follows naturally from the DOT team's presence in the SVST building. In addition, formal cooperation may be funded by the EU through an EU network. An eight-institute net EU work proposal has been submitted with myself as network coordinator, in which collaboration with the Swedish team on phase-diverse speckle restoration figures as a key item. The EU will announce its selections in September.

In addition, collaborations with other partners will continue and likely involve phase-diverse speckle tricks as well. The Lockheed group has hired Löfdahl, whose thesis contained the key Paxman *et al.* (1996) paper, and who has expressed willingness to assist. The IAC group at La Laguna is developing an extensive liquid-crystal polarimetry program. The Capodimonte group at Naples is concentrating on high-resolution magnetometry. The latter collaborations are also part of the EU network proposal.

Financing. "One may confidently expect that the most important bottleneck in this project will involve obtaining adequate financing (including funds for manpower that must be hired)." Indeed. I intend to apply for DOT-oriented programma-subsidie at the first opportunity. Speckle processing may be eligible for grants from computational physics. The speckle spectrometer may corner STW's interest and support.

My aim in these efforts is to make the most of the first DOT results. As the cover picture shows, the DOT images photogenically. I expect its imagery to be similarly striking.

7 Conclusion

AFEC II gave Utrecht solar physics high marks. It also applauded the DOT as an exciting prospect. And it concluded that there is an educational lack of instrumentation projects at the Dutch university institutes.

My prime consideration in this proposal is that speckle-restored imaging and speckle-restored spectrometry promise a revolution in solar physics. I would like to see these techniques in operation on scientific grounds. The prospect of beating the seeing even in polarimetry is tantalizing.

Second, the DOT is suited to be world leader in this development. Realization of these techniques exceeds the manpower and expertise available at Utrecht. In my opinion, these projects fit the NFRA environment admirably. They are not intrinsically different from other optical interferometry developments — thus not at the wayside.

Third, Utrecht continues to produce good students. It is to some extent regrettable to export observationally-interested ones abroad already at their graduation. The proposed projects are also educationally valuable.

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