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A Multi-Channel Speckle Imaging System for the DOT

P. Sütterlin, R.H. Hammerschlag, F.C.M. Bettonvil, R.J. Rutten

Sterrekundig Instituut, Postbus 80000, NL 3508 TA Utrecht, The Netherlands

V.I. Skomorovsky, G.N. Domyshev

Institute of Solar-Terrestrial Physics, 664033 Irkutsk, PO Box 4026, Russia

Abstract. The Dutch Open Telescope (DOT) had its initial observing campaign in September 1999. Although only a simple video system was used, the results demonstrated the excellent high-resolution capabilities of the combination of the open-telescope concept, the DOT optics, the La Palma site, and the speckle masking algorithm used to overcome the remaining image degradation due to the earth's atmosphere. The latter technique was therefore selected as primary DOT observing mode.

The DOT data-acquisition system is now being rebuilt into multi-channel imaging optics with fast digital 10-bit cameras and large-volume speckle burst storage. It will simultaneously map the deep photosphere in the G band and the chromosphere in Ca II K and Hα. In addition, trial Doppler imaging in the Ba II 4554 line with a narrow-band (80 mÅ) Lyot filter from Irkutsk is so promising that usage of this filter is now planned as well.

1. Introduction

The Dutch Open Telescope (DOT) is a unique and innovative solar telescope featuring an open design of both the telescope and the support tower. It is located close to the Swedish Vacuum Solar Telescope (SVST) on La Palma. Rutten (1999) and Rutten et al. (2001, these proceedings) give more detail on the DOT design and history. In this contribution we concentrate on the new DOT imaging system.

In September 1999 the DOT performed its first scientific observations in a joint campaign (JOP97) with the SVST, the VTT and GCT on Tenerife, and SOHO and TRACE. At the same time, these observations were a performance test for the main registration mode selected for the DOT, namely speckle burst acquisition with image reconstruction using the speckle masking method. Despite the simplicity of the setup (analog progressive-scan video camera. modem link and 8-bit video digitizer), the resulting images and movies show the high-resolution capabilities of this approach most impressively. The combination of an open telescope, an excellent site, and post-processing with the speckle masking method delivered diffraction-limited observations over extended durations.

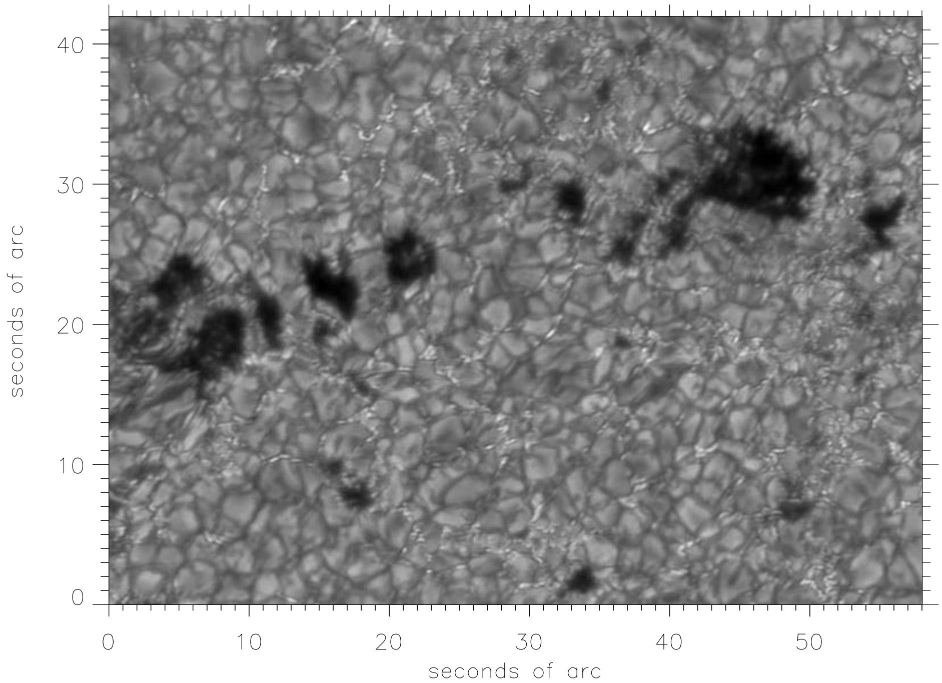

Figure 1. G-band image of AR 8700, September 19, 1999 12:14 UT.

Figure 1 shows an example reconstruction. The smallest structures are 0.2 arcsec, corresponding to the DOT resolution limit at 4300 Å. More DOT results are available on the DOT website[1], including a choice of superb G-band movies in which this resolution is reached consistently over long periods.

2. Speckle reconstruction

On the basis of the initial campaign, speckle burst acquisition and speckle reconstruction have been chosen as primary observing mode for the DOT in order to achieve diffraction-limited resolution already at only reasonable seeing. A major advantage of speckle reconstruction is that the whole field of view is restored.

We use the speckle masking method of Weigelt & Wirnitzer (1983). It was adapted to solar imaging by von der Lühe (1993) and further improved by de Boer (1995). It uses the fact that short-exposure images ($t \leq 10$ ms) freeze the atmospheric distortions while still showing signal at high spatial frequencies, although with statistically disturbed phases. By taking a large number of such short exposure images ("speckle burst") and using an elaborate statistical model one recovers the true amplitudes and phases in Fourier space and so regains the undisturbed image. The number of speckle frames one may collect is limited to the time in which the solar scene does not change, about 15–20 s for a pixel size

[1] http://dot.astro.uu.nl

of 0.1 arcsec and typical horizontal velocity of 4–5 km/s, or about 100 frames at 6 frames per second rate. This number is sufficient at reasonable conditions (Fried parameter $r_0 \geq 7\,\mathrm{cm}$), but when the seeing gets worse a much larger number of frames is needed for full restoration. This correlation between seeing quality and reconstruction quality implies that an excellent site is still needed to obtain long-duration sequences at desirable frequency.

3. Data-acquisition system

Wavelengths. The DOT science goal is to provide a link between ground-based high-resolution mapping of the magnetic topology of the solar photosphere and chromosphere and space-based short-wavelength imaging with missions as TRACE and SOHO which sample the transition region and corona. This will be achieved by simultaneous tomography of the lower solar atmosphere at different levels. We have selected the following wavelengths for this purpose:

- G band (width 10 Å), the molecular CH absorption band centered at 4304 Å, for locating and tracking small magnetic structures in the deep photosphere (see other contributions in these proceedings);
- continuum near the G band (width 10 Å), to allow easy discrimination between magnetic and non-magnetic brightenings;
- Ca II K line core (width 1 Å), for proxy magnetometry of the chromosphere and easy co-alignment with TRACE UV images;
- Hα line core (width 0.25 Å), to map magnetic canopies in the upper chromosphere;
- continuum near Hα (width 10 Å), needed to restore the Hα line-core images through two-channel deconvolution (see below).

Optical layout. High-resolution observing, even of the sun, is always short on photons. With 0.1 arcsec pixel size, 10 ms exposure time and 250 mÅ passband only a few thousand photons are collected so that care must be taken not to drown in random noise. The new secondary optics system of the DOT uses dichroic and polarizing beam splitters wherever possible. Figure 2 shows the layout schematically. The actual scheme is complex because it is not trivial to maintain the diffraction limit at widely different wavelengths using re-imaging lenses to match the $f/4$ primary to the desired 0.1 arcsec/px image scale. An alternative all-mirror scheme using a second parabola was discarded because of mechanical complexity.

Hα. The interpretation of narrow-band Hα filtergrams is difficult due to the crosstalk between brightness and Dopplershift modulation. To get meaningful information one has to obtain at least some profile information. At the DOT this will be accomplished by scanning through the line profile with a tunable Lyot filter on loan from the Canadian Research Council. We are planning to use five to seven samplings across the line as in Fig. 3. There won't be enough time to take 100-image speckle bursts at each, so that we plan to apply the two-channel restoration approach of Keller & von der Lühe (1992), using a nearby wider

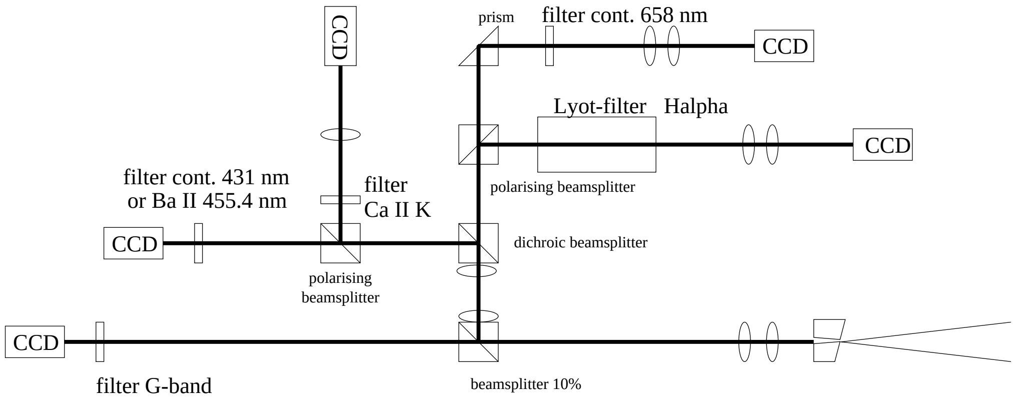

Figure 2. Optical layout of the new DOT five-channel imaging system. The parabolic primary ($D = 45$ cm, $f = 200$ cm) is to the right. A prime-focus pinhole in a water-cooled heat rejection mirror selects the field of view. The G-band channel lies along the telescope axis. The other channels will also be mounted at the top of the telescope but besides the incoming beam. Re-imaging lenses match the image resolution elements to the camera pixel size. The narrow-band filters are in telecentric positions. The Irkutsk Ba II 4554 birefringent filter may replace the near-G continuum filter.

continuum band to obtain speckle reconstructions and use these to determine the local point-spread function for deconvolution of the narrow-band Hα images.

Cameras, data links, storage. It is not easy to find cameras suited to speckle imaging. They must combine high speed with a reasonable dynamic range, a large number of pixels, high sensitivity in the blue, and affordability. We finally selected the Hitachi KPF-100, a machine-vision camera that uses the Sony ICX-85 chip. It has a 1296×1030 pixel chip, 10-bit digital output, and can deliver up to 12 frames per second. We use one PC (Compaq Proliant ML-350) with an IPC digital framegrabber board for each camera to control the camera, collect speckle bursts, and store these in a RAID array. Each PC has a storage capacity of 72 Gb; with all five cameras running at full speed the total 360 Gb fills up in 1.25 hours, with the standard cadence of two bursts per minute the DOT is able to observe for two and a half hours. Data backup is done to an Exabyte Mammoth-2 with a 7-cartridge tape library.

The data links required special care since the DOT is operated from the SVST building over 100 m away, much further than the 3 m separation normally allowed between camera and frame grabber. Special connection hardware using optical fibers built by the Utrecht workshop IGF serves for camera control and data transfer. IGF constructed the software user interface as well.

The cameras have 6.7 μm square pixels. The re-magnification by the secondary optics gives an image scale of 0.07 arcsec per pixel and fully samples the 0.2 arcsec theoretical resolution limit even along the diagonal in the G band (4304 Å). This is not fully the case at Ca II K (3933 Å) but the chromospheric

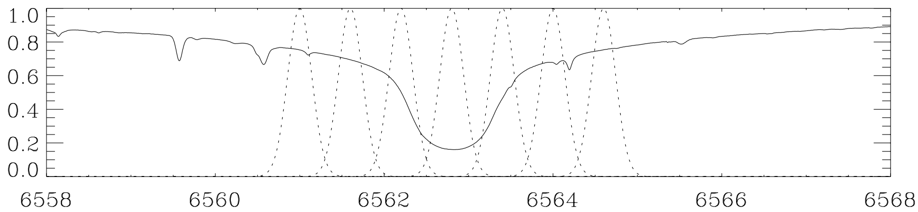

Figure 3. Five to seven narrow-band filtergrams across Hα allow to separate Dopplershift and brightness variations. Wavelengths in Å.

brightness structure seen in this line is intrinsically fuzzier due to resonance scattering. The full field of view amounts to 92×73 arcsec at this pixel size.

4. Ba II 4554 Dopplergrams

The Russian co-authors to this contribution were invited at the suggestion of A. Ludmany (Debrecen) to bring their birefringent Lyot filter to La Palma for an initial test at the SVST. The filter selects extremely narrow passbands (80 mÅ) in either Ba II 4554 or Hβ. The barium resonance line has the same atomic configuration as Ca II K but has much larger atomic weight, much lower chemical abundance, and extensive hyperfine and isotope splitting (Rutten 1978). Its equivalent width is 159 mÅ.

Our test of this filter at the SVST with the DOT video camera was highly promising. It showed that despite the narrow bandwidth speckle reconstructions are feasible at 45 cm aperture. The resulting Dopplergrams are sufficiently interesting to be presented here.

The filter was tuned to five wavelength positions, spread symmetrically around line center at 35 mÅ intervals (Fig. 5). A speckle burst of 100 video frames was taken at each position before retuning the filter to the next one. Figure 4 shows an example of one such scan after reconstruction with the speckle masking method. The differences between the two line wings are striking. In the red wing granulation is very prominent, whereas the granular contrast is low in the blue wing. This is a consequence of the granular velocity-intensity correlation: the gas moves upward in bright granules, down in dark lanes (see cartoon in Fig. 5). The situation reverses when there is an inverse brightness-intensity correlation, i. e. when bright structures contain downward motion. This is the case for many small, bright features seen in the inner blue-wing image. These undoubtedly correspond to G-band bright points marking tiny magnetic field concentrations in intergranular lanes. Their blue-wing brightness implies downdrafts in and/or around these.

By carefully aligning the five images of one scan and fitting the line profile per pixel we obtain Doppler maps of which one is shown in Fig. 6. It quantifies that blue-wing bright points exhibit downflows of 1–1.5 km/s. Combining such

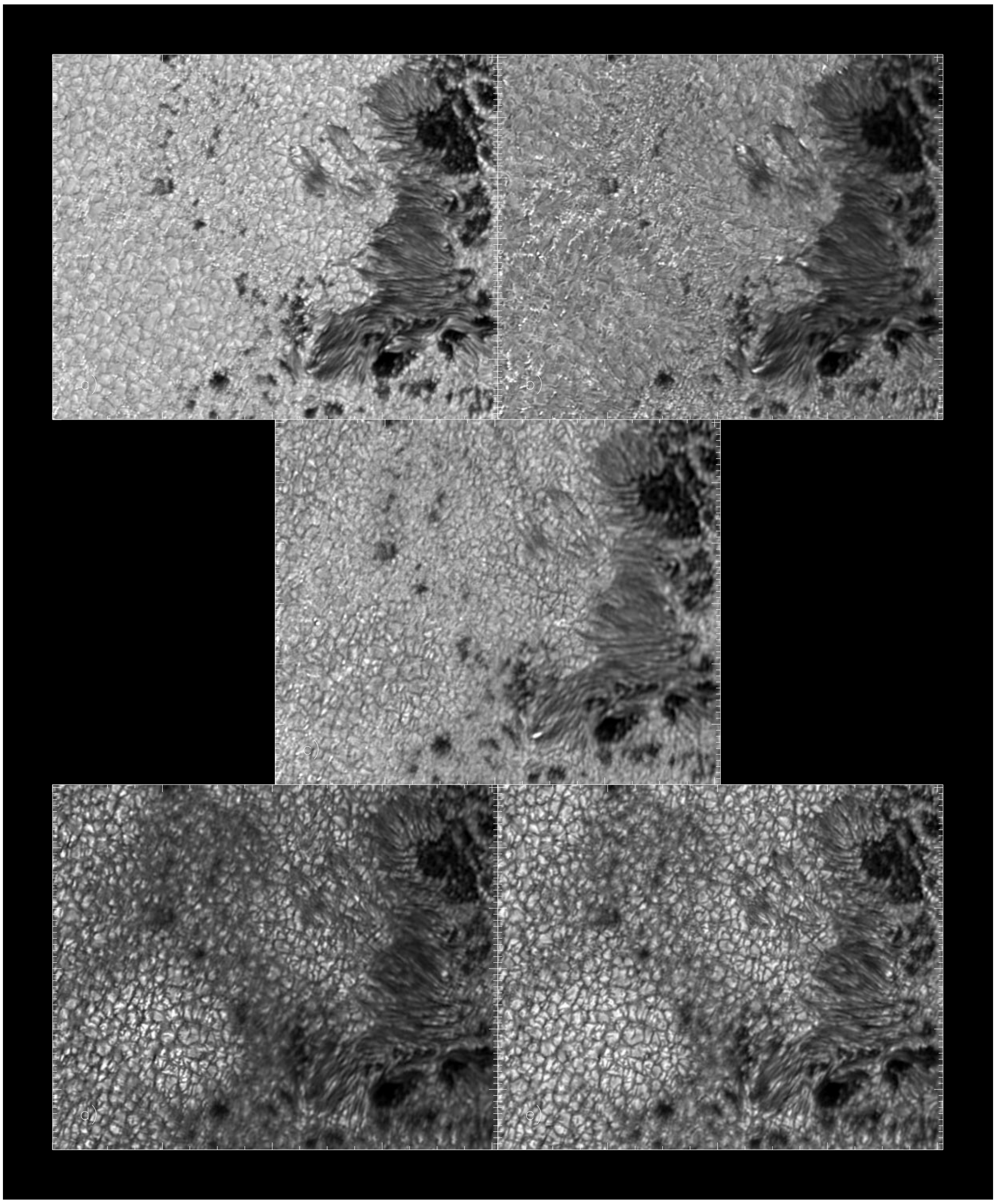

Figure 4. A five-point speckle-restored scan through the barium line showing AR 9077 on July 15, 1999. Field size is 80×60 arcsec^2. a) –70 mÅ. b) –35 mÅ. c) line center. d) +35 mÅ. e) +70 mÅ. The lower-left part of the field contains quiet sun with normal granulation (clearest in the red wing). The plage area running across the middle of the field is dark in the red wing. The inner blue wing (second image) displays filigree grains in intergranular lanes.

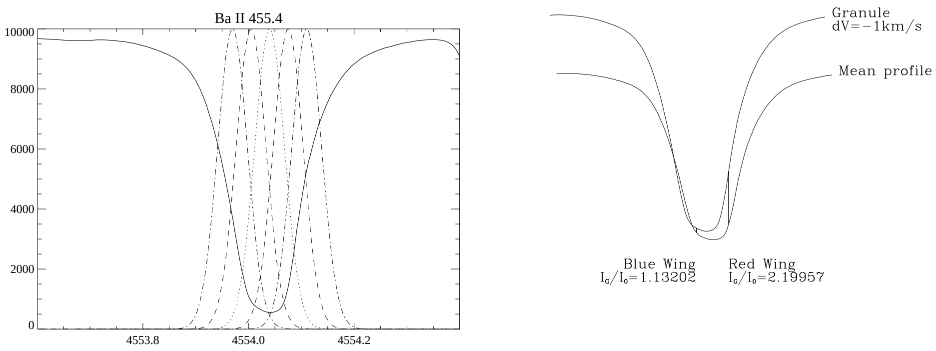

Figure 5. Left: five passband settings covering the Ba II 4554 line. The line has a boxy asymmetrical core due to hyperfine and isotope splitting. Wavelengths in nm. Right: correlation between brightness and upward motion enhances the contrast in a red-wing filtergram.

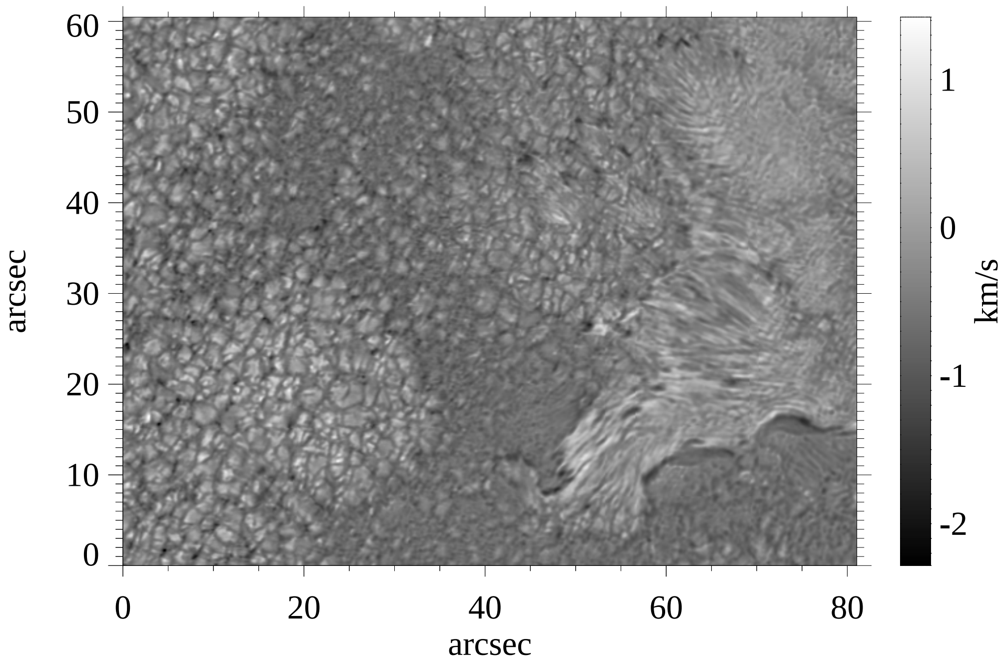

Figure 6. Doppler map of AR 9077 derived from the images in Fig. 4. Sign: downward velocity negative (dark, see scale at right).

high-resolution Doppler maps with high-resolution G-band images offers the possibility to observe e. g. convective collapse on small scales.

The Doppler map also reveals an extended dark region with an average redshift of approximately 400 m/s. Comparison with the images in Fig. 4 suggests that this is a plage area containing abnormal granulation. Its signature in the Doppler map indicates that the barium line flanks are highly sensitive to the corresponding velocity pattern. We suspect that this sensitivity follows from the combination of large atomic mass (small thermal Dopplerwidth) and high angular resolution (doing away with "microturbulence" = unresolved motions).

5. Outlook

The first components of the new data acquisition system were installed in November 2000. They include the G-band optics, G-band camera, fiber link, and computer system. The remaining parts will follow successively in 2001, starting with the blue continuum and the Ca II K channels. Following the promising results from the barium test, the mechanical layout of the secondary optics was adapted to allow telecentric installation of the Irkutsk filter in the DOT as well; it should give insights in photospheric dynamics on scales as small as 100 km. Hopefully, the full system will be up and running by the autumn of 2001. If so, speed-up of the speckle processing through parallel computing will become our next priority concern. In addition, Ba II 4554 polarimetry may prove fruitful.

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