Chapter 1

THE DUTCH OPEN TELESCOPE

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Abstract The Dutch Open Telescope (DOT) is an innovative optical solar telescope at the Roque de los Muchachos Observatory in the Canary Islands. Its angular resolution reaches the diffraction limit of the 45 cm aperture (0.2 arcsec in the visible) through combining an excellent wind-swept site, a fully open design of the telescope and support tower, sufficient mechanical rigidity to rely on wind flushing without shake, and consistent application of speckle imaging and reconstruction in all data acquisition. Its successful demonstration of the open-telescope principle presently inspires major solar-telescope projects aiming at adaptively corrected spectropolarimetry. The DOT science niche consist of high-resolution large-field tomography of the solar photosphere and chromosphere, and will remain one in which small telescopes excel.

Keywords: Solar physics, optical telescopes, speckle reconstruction

1. Introduction

The Dutch Open Telescope (DOT) on La Palma is a small telescope that successfully aims at tomographic high-resolution imaging of the solar photosphere and chromosphere. Its open concept is now followed in ambitious large-telescope projects in Europe (GREGOR) and the US (ATST). It is presently being equipped with a five-camera data acquisition system that enables large-volume (350 Gb/day) speckle recording. The combination of an excellent site, excellent telescope and consistent image restoration makes the DOT the European counterpart to the US Big Bear Solar Observatory where the same combination is pursued (cf. Goode's section on p. ?? *ff*). I discuss the nature and future of the corresponding science niche after placing it in large-telescope context, in particular comparing speckle reconstruction with adaptive optics, and presenting DOT details.

2. Solar telescope context

All solar optical telescopes are small compared with nighttime telescopes. The only one presently exceeding 1 m diameter is the McMath-Pierce on Kitt Peak (1.5 m) which should not be counted as "telescope" in the literal sense of being a sharp imager. In the visible it is primarily a photon collector for Fourier spectrometry and spectropolarimetry with high spectral purity but with low angular resolution, far below the theoretical diffraction limit. The next largest (90 cm) solar telescope is the French-Italian THEMIS on Tenerife which also does not reach its theoretical diffraction limit.

The Dutch Open Telescope (DOT) described here has a primary mirror of only 45 cm diameter but is not a small telescope in performance. It has taken over the role of providing solar images at nearly 0.2 arcsec resolution from the former Swedish Vacuum Solar Telescope (SVST) on La Palma. The latter was a refractor of similar aperture (48 cm) and has widely been acclaimed as the sharpest solar telescope over the past decade. The DOT, which is located at the same site and is operated from the Swedish building, now delivers solar imagery of the same quality. The reason why these "small" telescopes are effectively not small is that even at La Palma the Fried parameter r_0 describing atmospheric quality in terms of equivalent telescope aperture exceeds 20 cm only occasionally. Super-seeing commensurate with meter-class aperture may occur in perfect La Palma weather but waiting for that might take many years. Even half-meter telescopes are usually far too large. The same holds at the best US site, Big Bear (Goode et al. 2000). With respect to angular resolution there is no point in building larger solar telescopes if the atmospheric deterioration is not corrected — or avoided by going to space.

Much better image quality than the La Palma site furnishes at non-super times was obtained at the SVST through phase-diverse image registration (Löfdahl & Scharmer 1994, Paxman et al. 1996, Löfdahl et al. 1998) and is now reached at the DOT through speckle burst registration (Sütterlin et al. 2001a). Both techniques produce image quality close to the theoretical diffraction limit already when the seeing is only reasonable ($r_0 > 6$ cm) at the cost of elaborate off-line image reconstruction. The latter starts with tessellating the observed field in isoplanatic subfields which are reconstructed independently and then rejoined. The total field of view is therefore limited by the camera chip (or the field stop or the optics quality) but not by the image restoration technique. A drawback of phase-diverse and speckle reconstruction is the large amount of subsequent processing. A basic limitation is that their effectiveness diminishes with aperture size, larger aperture requiring better seeing to begin with.

The alternative to post-detection reconstruction is adaptive optics in which the wavefront is corrected on-line. Its advent presently revamps groundbased solar physics just as it revolutionizes groundbased nighttime astronomy (but with the important difference that the sun is a very extended low-contrast object, granulation and other small structure serving as wavefront encoder rather than natural or artificial point stars). Adaptive optics makes it feasible and desirable to build meter-class and larger solar telescopes, presently leading to a new wave of solar telescope building. The successor to the SVST, the New Swedish Solar Telescope (NSST), will be a 96 cm vacuum refractor operational in 2002. The German Gregory Coudé Telescope (GCT) will be retrofit with an open 1.5 m Gregorian feed telescope into GREGOR by about 2005. The US National Solar Observatory leads the Advanced Technology Solar Telescope (ATST) enterprise, aiming at an open 4 m aperture reflector by about 2010. All three telescopes will utilize adaptive optics (as will, hopefully, THEMIS do at some stage).

How do speckle reconstruction and adaptive optics compare? Basically, speckle reconstruction divides the image plane into subfields smaller than the isoplanatic patch and restores each by fitting a seeing-sampling sequence of perturbed images (“speckle burst”) with a model of atmospheric turbulence. Each patch sees the whole pupil; larger aperture averages the wavefront corrugation wider so that the speckle S/N in the image plane goes down. Adaptive optics instead divides the pupil plane into subapertures smaller than r_0 and corrects the wavefront for each, but only the on-axis isoplanatic patch optimally. Adaptive-optics system multiplication for other directions would be impractical; a better option is multiconjugate adaptive optics in which tomography of the seeing layers increases the isoplanatic patch (*e.g.,* Beckers 1989, 2000). Combination of these complementary pupil and image plane techniques is obviously attractive for wide-band imaging with large telescopes, but is less easily realized for narrow-band and slit-limited applications.

Note that even if the aperture exceeds 1 m considerably, the attainable angular resolution does not keep pace. Aperture increase does not change the photon flux per diffraction-limited resolution element whereas the permitted integration time (set by the solar scene change speed, *e.g.,* the sound speed) diminishes with increasing resolution. The number of photons available for detection therefore goes actually down with increasing aperture! The need for much larger aperture like the ATST’s envisaged 4 m comes from the requirement to feed sufficient photon flux into spectrometers, full-Stokes spectropolarimeters and tunable Fabry-Perot interferometers whose narrow bandpasses decimate the photon take spectrally and whose application often requires very high S/N (as in polarimetry where images or spectra using only a small fraction of the light are subtracted). These solar applications are photon-starved, which may sound surprising to nighttime astronomers but at high angular resolution the quantity to consider is intensity, not irradiance flux, and the solar intensity is just as low as from any other cool star. In these photon-limited applications optimal wavefront correction means restoring as many Zernike coefficients as the system order can reliably handle at a given angular resolution, say 0.1 arcsec. Large-aperture adaptive optics makes it now possible to reach such meter-class resolution at reasonable system order in the visible with enough S/N for quantitative spectral-line diagnostics, indeed constituting a major revolution. Multiconjugate adaptive optics may increase the effective isoplanatic patch. Note that the (considerable) spread function tails are corrected well only at high system order; adaptive optics will work best for bright structures in a dark field.

Thus, small solar telescopes may exploit a high-resolution niche by full-field imaging and subsequent reconstruction at 0.2 arcsec resolution, whereas adaptive optics should enable large solar telescopes to achieve about 0.1 arcsec resolution over small fields in narrowband diagnostics such as Stokes spectropolarimetry. It would be a waste of money to let them fill the small-telescope niche.

Obviously, if money were no concern both small and large optical solar telescopes are much better off in space where the seeing is optics-limited, weather is perfect apart from particle storms, nights are rare (in polar orbits) or absent (in L1 orbits), and where co-pointing with EUV and X-ray instruments is relatively easy. Since money is a concern, only small telescopes make it to space while 1 m telescopes so far do not climb beyond high-altitude balloons (Flare Genesis, Sunrise proposal). The 50 cm diameter Solar-B telescope, slated for launch into polar orbit in 2005, may be seen as the SVST or DOT in space combined with a spectropolarimeter emulating the HAO/NSO Advanced Stokes Polarimeter currently at the Sacramento Peak Dunn telescope. The niche which Solar-B will leave for small telescopes on the ground is to team up, for example in observing the other end of coronal loops at the same time or in employing diagnostics not implemented in Solar-B to the same field, and to try out newer technology and more daring tricks than permitted in space.

3. DOT approach

The DOT was built by R.H. Hammerschlag and coworkers using the university workshops at Utrecht and Delft at the instigation of the late C. Zwaan (1928–1999). Zwaan was heavily involved in the Europe-wide site testing by the Joint Organisation for Solar Observations which in the 1970's led to the selection of the Canary Island volcanoes as best European location with respect to daytime seeing. In particular at the Roque de los Muchachos Observatory on La Palma, the best daytime seeing tends to occur when the trade wind blows sufficiently strong upslope from Northern directions to confine the turbulent convection that results from solar heating to a thin boundary layer of only 10 m thickness. Above this layer the trade wind can be fairly laminar, resulting in excellent local seeing conditions that may last all day. In addition, upper-atmosphere jet streams which often cause high-altitude shear layers at higher latitudes pass only rarely over the Canary Islands; indeed, the La Palma nighttime seeing (generally a lower limit to daytime seeing) is frequently excellent (outside the nighttime domes). In appreciation of the trade wind's benign influence Zwaan and Hammerschlag worked out an open telescope to be mounted on an equally open 15 m high tower, designed to minimize local disturbance of the trade wind and to permit the latter to flush

Figure 1.1. Hammerschlag's Dutch Open Telescope on La Palma. Left: telescope with 45 cm primary mirror and support tower, open to the trade wind from the North (to the right) which brings the best seeing. The inversion layer (clouds) is far below the 2400 m high volcano rim. The clamshell bad-weather canopy is folded away. The white box contains a water tank for prime-focus cooling. The pipe transports control commands and digital images from/to the control room in the Swedish telescope building. Right: the parallactic telescope mount is extraordinarily heavy and stiff to avoid image shake from wind buffeting. The slender on-axis pipe at the top contains a water-cooled tilted mirror which reflects the primary solar image away except for a 1.6 mm hole transmitting the 2 arcmin field of view to the focusing mechanism, re-imaging optics, G-band filter and CCD camera. More photographs at http://dot.astro.uu.nl.

the telescope, including the primary mirror, from solar-induced internal seeing. Its realization by Hammerschlag in the subsequent decades took much innovative engineering in order to match the open concept with sufficient mechanical rigidity to withstand strong and highly variable wind loads (Hammerschlag 1981, Hammerschlag & Bettonvil 1998). The result is portrayed in Fig. 1.1. A sample image from the DOT is shown in Fig. 1.2; more DOT images and movies are available at http://dot.astro.uu.nl.

The DOT tower consists of steel tubes in a framework of four triangles supporting a conical frame on which the telescope and platform rest. At a weight of 13 tons the tower is considerably lighter than the 17-ton telescope itself and is not

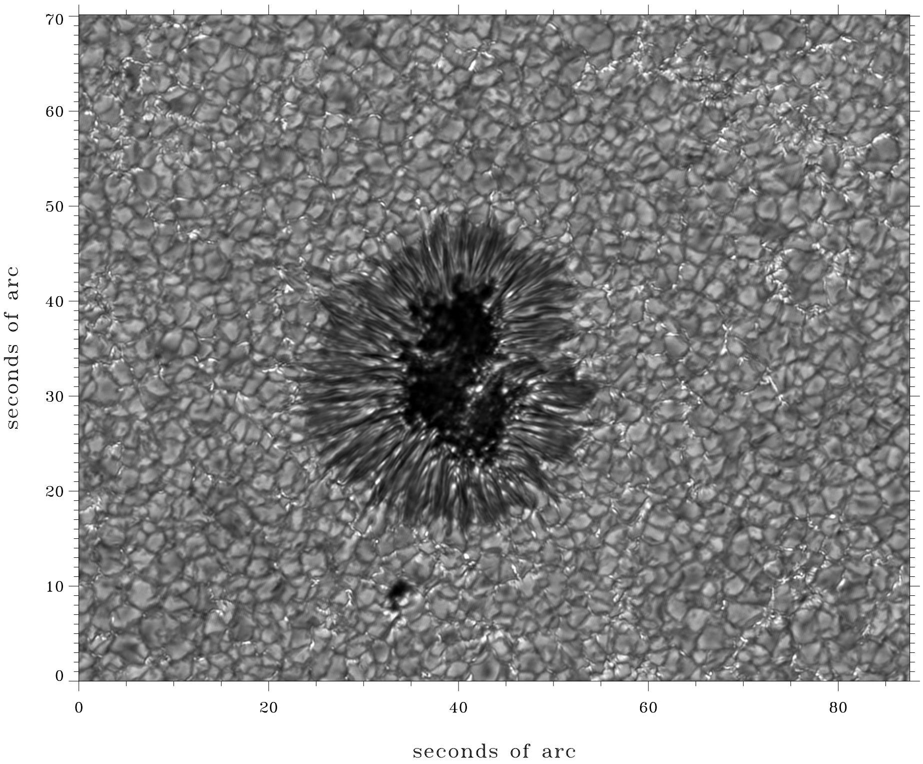

Figure 1.2. G-band image of sunspot AR 9407 taken with the DOT on April 1, 2001 by P. Sütterlin using the first camera of the multi-channel imaging system. The tiny white specks in intergranular lanes mark kilo-Gauss fluxtubes and only become visible at better than 0.5 arcsec resolution. The full one-hour movie sequence is available at http://dot.astro.uu.nl.

stiff against wind loads, but the triangle arrangement permits only planar motion of the platform while inhibiting tilts. The orientation toward the sun remains the same even in strong wind buffeting. The tower is also designed to withstand large ice loads, an inclement weather characteristic of the La Palma site. The staircase and elevator cage may fill up with 30 tons of ice!

The telescope itself is simply a parabolic mirror in a parallactic mount. The mirror (currently Cervit, 45 cm diameter, focal length 200 cm, but the mechanical structure would accept a larger diameter) is supported deformation-free with nine-point axial and three-point radial support levers. The incoming beam is focused onto a water-cooled field stop that reflects most of the primary image out of the telescope. The parallactic mount is considerably overdimensioned as well as unbalanced in order to obtain extreme pointing stability at very low heat dissipation (only about 20 W). Brushless pairs of servo motors in push-pull preload configuration without backlash drive four-step gear trains achieving 1:75,000 reduction with large self-aligning gear wheels. They maintain precise pointing even in the strong good-seeing winds (typically 10 m/s).

The clamshell canopy has a diameter of 7 m and folds away to the sides. It is made of heavy polyester fabric mounted on massive steel ribs, can still be closed in winds up to 30 m/s, and should then withstand 70 m/s (Beaufort 12) winds. The coated surface tends to remain ice-free.

The DOT demonstrated soon after its first light (autumn 1997) with a simple video camera that the open-telescope concept can successfully replace the vacuum solution to internal seeing that has been used so far in high-resolution solar telescopes. This breakthrough success of the open principle is now being copied in the GREGOR and ATST projects. It also generated funding to implement secondary optics and data acquisition systems to enhance and exploit the DOT science capabilities. They are currently being completed and consist of multi-channel optics to feed solar images at different wavelengths simultaneously to five CCD cameras in order to realize “tomographic” imaging of the deep photosphere using the G band around 4305 Å, of the low chromosphere using the core of Ca II K at 3933 Å, and of the high chromosphere using a rapidly tunable Lyotfilter in Hα at 6563 Å. The G-band optics and camera are located on-axis behind the water-cooled field stop (Fig. 1.1). The other beams, presently being installed by by R.H. Hammerschlag and F.C.M. Bettonvil, will branch off after the focusing mechanism to optics platforms mounted at the top of the telescope besides the incoming beam. The digital frames from the five cameras are transported by optical fiber to the control room in the nearby Swedish telescope building.

Extensive tests by P. Sütterlin with the initial DOT video camera demonstrated also that speckle burst acquisition and restoration are a viable and desirable way to improve the frequency of diffraction-limited observing considerably. Sütterlin and the Physics Instrumentation Group at Utrecht subsequently installed a large-volume speckle-burst acquisition system. The five Hitachi KP-F100 cameras (1296$\times$1030 px, 10 bits) are always run in synchronous speckle mode, each camera obtaining 100–200 frame bursts at up to 11 frames/s rate and storing these via its own fiber link and PC on a 70 Gb RAID array. The RAID disks are copied out to an Exabyte Mammoth-2 tape library with 350 Gb capacity. The two extra cameras will enable multi-channel speckle restoration following Keller & von der Lühe (1992) in which wide-band wavefront estimation is used to restore narrow-band frames that by themselves have insufficient S/N within the exposure limit set by the 10 ms seeing freeze time. Another aim is to use an Irkutsk-built Lyot filter tuning through the Ba II 4554 Å line which is an excellent Doppler diagnostic (Sütterlin et al. 2001b).

The next step will be to embark on parallel processing to handle the speckle data stream overnight or in near-real-time following the Big Bear example of Yang et al. (2001). With the advent of affordable Beowulf clusters and high-speed networks this seems a realistic goal even for a small low-budget university group.

4. DOT science context

With the five-camera speckle system the DOT indeed fills the niche of high-resolution imaging open to small telescopes while the upcoming larger telescopes exploit adaptive optics for spectropolarimetry, and it does so tomographically up to the height of Hα formation. What science fills this niche?

The holy grail of high-resolution imaging of the solar surface is to nail down the structure, dynamics and evolution of the slender kilo-Gauss magnetic fluxtubes that appear to be the basic building blocks of solar magnetism at the bottom of the solar atmosphere. Their cross-sections measure only 0.1–0.2 arcsec or less. They figure strongly in the science rationales of the GREGOR, Sunrise, ATST, and all other high-resolution solar physics proposals. The DOT has laid its claim to SVST-successorship the past years by imaging them in spectacular G-band movies sampled by Fig. 1.2. At 0.2 arcsec resolution the fluxtubes ("magnetic elements") are at least seen if not resolved; their visibility vanishes already at 0.5 arcsec resolution through cancellation of their excess brightness against the surrounding dark intergranular lane (Title & Berger 1996). However, imaging alone does not suffice to detail their nature; additional high-resolution Stokes spectropolarimetry and Doppler mapping must indeed be supplied by larger telescopes using adaptive optics or located above the atmosphere. The same holds for other high-resolution topics such as sunspot dynamics and filament physics.

Large-telescope high-resolution spectropolarimetry will only address the photosphere, perhaps going up a few hundred km though using Hanle depolarization (of once-scattered resonance lines near the limb) and infrared diagnostics such as the Mg I 12 micron lines. The solar atmosphere extends much higher and changes considerably on the way, particularly due to the plasma-beta flip from gas pressure domination to field domination. In the coronal regime the EUV movies from SOHO's EIT and from TRACE vividly display the fine scale and dynamic character of the magnetically constrained coronal topology. The latter ultimately depends on photospheric boundary conditions such as flux emergence, dispersal and disappearance as well as "footpoint" dynamics, but the actual connection between, say, photospheric tubes and coronal loops is totally enigmatic. The fluxtube paradigm prescribes field expansion into magnetic canopies that spread field homogeneously throughout the atmosphere already in the low chromosphere. Coronal loops delineate very long and very slender field configurations at specific temperature that become visible through density contrasts. In between, observations in Hα and EUV lines indicate a plethora of low-lying finely-scaled structures with rapid large-amplitude dynamical changes.

High-resolution tomography, in particular using Hα to define the actual canopy structure, can be the missing link to fill the gap between tubes and loops. The Hα line is about the only groundbased diagnostic that permits canopy mapping. Quantitative interpretation of Hα filtergrams is notoriously difficult (the line mixes Dopplershifts with brightness modulation and is awkwardly sensitive to NLTE population mechanisms depending on both density and temperature) and shows both optically thick and optically thin structures. These mixtures give high-resolution Hα movies their dramatic appearance but also make them hard to interpret. Detailed numerical line formation modeling must accompany Hα imaging to deliver quantitative maps of the chromospheric topology, in concert with photospheric Dopplergrams and magnetograms and EUV and X-ray coronal imaging. This is a major quest for the DOT and similar high-resolution imagers. I believe that supplying atmospheric tomography including quantitative Hα diagnostics at high resolution in concerted multi-wavelength campaigns represents an important solar physics niche for small solar telescopes to fill for years to come.

Interest in the electrodynamical coupling between the low and high solar atmosphere transcends solar physics and cool-star astrophysics because this connection figures also in the coupling of solar activity, via the solar wind and more incidental excess particle losses as in coronal mass ejections, to the earth environment and terrestrial climate.

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