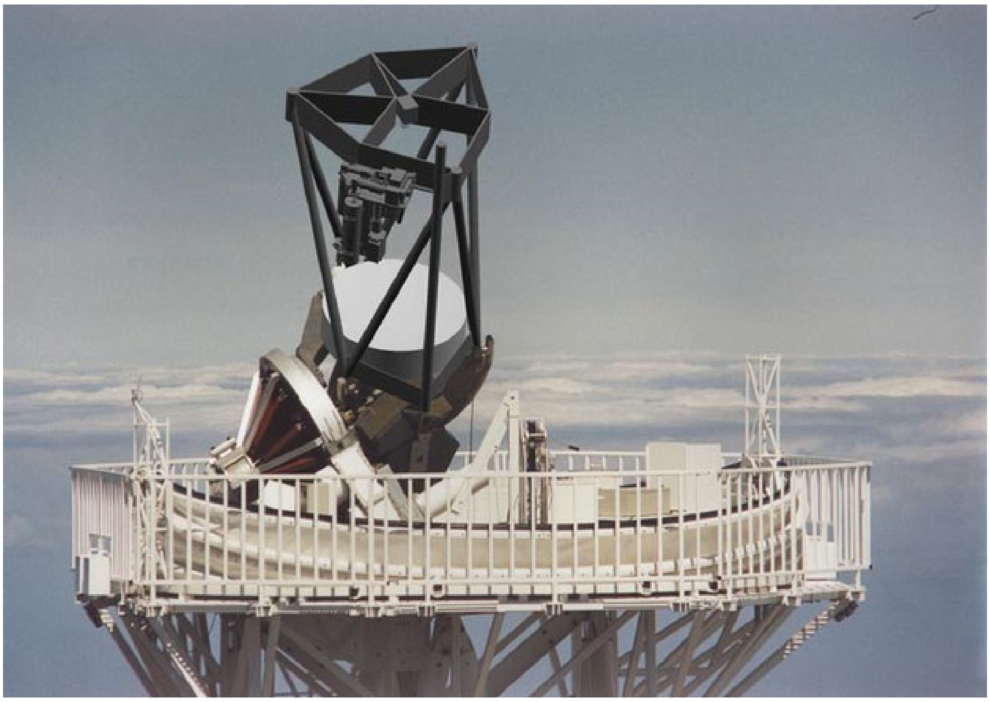
DOT^{++} SOLAR PHYSICS

Proposal for NOVA phase 2

Submitted March 3, 2003



DOT^{++} design drawing superimposed on a DOT photograph

Contents

1 Executive summary

The *Dutch Open Telescope* (DOT; `http://dot.astro.uu.nl`) on La Palma is a revolutionary telescope achieving high-resolution imaging of the solar surface. The DOT combines a pioneering open design at an excellent wind-swept site with consistent image restoration through speckle interferometry. By 2005 the DOT will fill a major solar physics niche as the premier $0.2''$ tomographic mapper of the solar atmosphere, frequently sharing in international multi-telescope campaigns through student-serviced time allocation.

This DOT^{++} proposal requests support to triple the DOT resolution by increasing the aperture to 140 cm (2005–2007) and to triple the field diameter by renovating the cameras and speckle processing (2007–2008).

The design permits versatile operational trade-off choice between angular resolution (down to $0.07''$) and field size (up to $300''$).

The proposed double tripling of this Dutch telescope achieves resolution well beyond the Solar-B imaging capability from space, and will maintain the DOT's science value as tomographic context imager in nearly any solar observing campaign, fully complementary to $0.1''$ adaptive-optics spectropolarimetry and $0.1''$ ultraviolet imaging and spectrometry with groundbased telescopes and space missions that are now being built or in the proposal stage.

2 PI and co-applicants

The personnel table below specifies the present DOT team, with vacancies. All are 100% involved in DOT efforts and research excepting teaching duties.

name	title	role	employer	period
R.J. Rutten[a]	Prof. Dr.	PI	UU (SIU), ITA	until medio 2007
N.N.[b]	Prof. Dr.	program leader[c]	UU (SIU)	2004–2010+
F.C.M. Bettonvil	Ir.	project manager	ASTRON (NWO)	until 30-09-2005
R.H. Hammerschlag	Dr. Ir.	project engineer	UU (SIU)	until 2009
P.W. Hoogendoorn	Mr.	project technician	UU (IGF)	until late 2008
P. Sütterlin	Dr.	solar physics, speckle	UU (NWO)	until 30-4-2004
K. Tziotziou	Dr.	solar physics, inversion	UU (EC-ESMN)	01-03-2003 – 30-09-2005
A.G. de Wijn	Drs.	solar physics	UU (AIO)	until 30-09-2006
candidate identified	Drs.	solar physics	UU (AIO)	01-09-2003 – 30-08-2007

[a]Ad-interim program leader; visiting professor, Institute of Theoretical Astrophysics, Oslo
[b]Search started
[c]Possibly future PI, depending on interest

This team constitutes the *Solar Astronomy Program* initiated on December 15, 2002 by the Faculteit Natuur- en Sterrenkunde (FacNS) of Utrecht University (UU), as a separate administrative entity within the Sterrekundig Instituut Utrecht (SIU). The FacNS objective is to exploit the success of the DOT, expand UU solar physics, and revive the long-standing Utrecht tradition of excellence in this field. FacNS has given green light for the instatement of a new chair in solar physics. It is highly likely, also in view of present candidates, that the incumbent will, as Solar Astronomy Program leader, strongly support the DOT project and this proposal.

The personnel table also shows that the present team is small relative to the project ambition and vulnerable through temporary contracts and approaching retirements. It is anticipated that the professor will aggressively seek program expansion locally, nationally, and internationally, and that, additionally to this proposal, NOVA2 will permit "dakpan" appointments for the two retirees (who will not seek early retirement). The present proposal assumes that the Utrecht Solar Astronomy program will indeed expand and that the DOT team continues throughout 2004–2008 at least at current strength. The FacNS willingness will obviously hinge on the longer-term DOT prospects.

3 Science case

Solar physics context. Solar physics is largely directed towards gaining understanding of the complex magnetohydrodynamical nature of solar activity. Solar magnetic fields are generated by enigmatic dynamo processes in the solar interior, organized into intricate activity patterns in the photosphere, dominate the structure of the chromosphere and corona at all spatial and temporal scales, regulate the solar wind, and affect the extended heliosphere including our own environment. Solar physics presently flourishes in a remarkable renaissance thanks to continuous high-cadence space observing (SOHO, TRACE), increasingly realistic numerical simulations, increasing interest in space weather, and new groundbased observing techniques. This proposal exploits the latter to give Dutch astrophysics a unique position in this renaissance during the second half of the decade when GREGOR, Solar-B, SDO and presently proposed other instruments will set the stage.

Magnetism is the key. Photospheric magnetism, varying from slender kilo-Gauss flux tubes in intergranular lanes that represent the basic building block up to sunspots and whole active regions, constrains the topological structure and dynamics of the outer solar atmosphere, from the upper chromosphere through the transition region and corona out to the solar wind and extended heliosphere. The tube motions dictated by (sub-)surface convection in a variety of temporal and spatial scales impart topological and dynamical constraints to the closed loops and open field bundles constituting the corona. This electrodynamical coupling of the outer atmosphere to the solar surface has become a key area of solar research. It transcends solar physics *per se* because via the solar wind, cosmic ray modulation and coronal mass ejections, the coupling extends to the earth neighborhood and possibly even the terrestrial climate.

Specific research topics within the proposal context are:

- solar surface fields: fluxtube patterns, fluxtube dynamics, magnetic carpet topology and maintenance, sunspot structure and oscillations, prominence stability and eruptions, flares;
- topology and evolution of active regions: plage emergence and disappearance, eruption precursor geometry, sunspot breakup;
- canopy transitions: wave penetration and heating, moss structure and dynamics, tube-loop coupling.

The corona movies from SOHO and TRACE and the photosphere movies from DOT dramatically convey the dynamical nature of the magnetically-constrained solar atmosphere. They demonstrate forcefully that high-resolution large-field high-cadence long-duration observation is

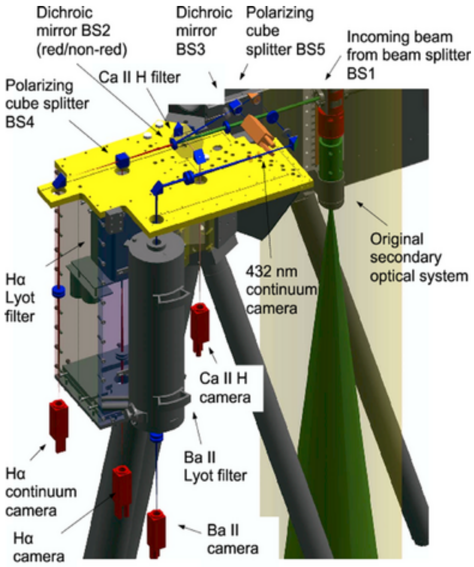


Figure 1: Left: Dutch Open Telescope on La Palma. The DOT is mounted on a 15-m high open tower to exploit the superior atmospheric seeing brought by the oceanic trade winds. The clamshell bad-weather canopy is folded away in this view. The 45-cm parabolic primary mirror is seen at the center of the telescope structure. The post-focus system is mounted at the telescope top. The digital image stream is transported through fibers to the control room in the nearby Swedish SST building. Right: optics diagram of the tomographic multi-wavelength system feeding six identical speckle cameras synchronously with speckle bursts in the blue continuum (432.0 nm, deep photosphere, granulation), red continuum (651.0 nm, linear Rayleigh-Jeans temperature sensitivity, wide-band reference for Hα restoration), G band (430.5 nm, molecular CH lines showing photospheric fluxtubes at enhanced contrast; this channel is mounted separately in the on-axis tube seen in the photograph), Ca II H (396.8 nm, low-chromosphere magnetism, well-suited for precise co-registration with ultraviolet images from space), Hα (656.3 nm, low-lying loops in magnetic canopies) and Ba II (455.4 nm, heavy-ion line optimally suited to Doppler and Hanle mapping). The latter two channels use large tunable Lyot filters.

a must: *"solar physics becomes a science of movies"*. In addition, holistic strategies combining many different diagnostics (Stokes vector polarimetry, Doppler mapping, EUV imaging) with multi-layer tomography are a must as well: much solar observing is now done in international multi-telescope campaigns with common targeting. In this arena, the DOT's niche is to supply wide-field high-resolution movies sampling the lower atmosphere from the deep photosphere to the high chromosphere through synchronous multi-wavelength speckle imaging.

Solar physics with the DOT. The DOT was designed and built by Hammerschlag with coworkers at Utrecht and the university workshops at Delft and Utrecht. The open concept was revolutionary. So far, all high-resolution solar telescopes use evacuation to avoid internal turbulence caused by focus heating. The open DOT instead relies on telescope flushing by the strong laminar trade winds which make La Palma a world-class solar site. The DOT's successful demonstration of this principle together with the maturing of adaptive optics spawned a wave of new large-telescope projects elsewhere[1].

The DOT is at the forefront in a high-resolution revolution in which diffraction-limited solar observing is achieved rather than only Fried-parameter resolution (usually below 15-cm effective aperture even on La Palma). The former Swedish telescope on La Palma (SVST, 48 cm) was

[1]The new open telescopes break the 1-m limit imposed on vacuum windows and refractor objectives by glass technology. The newly rebuilt Swedish 1-m Solar Telescope (SST) on La Palma, from whose building the DOT is operated, represents the largest feasible refractor. All larger-telescope projects concern open reflectors (Sect. 6).

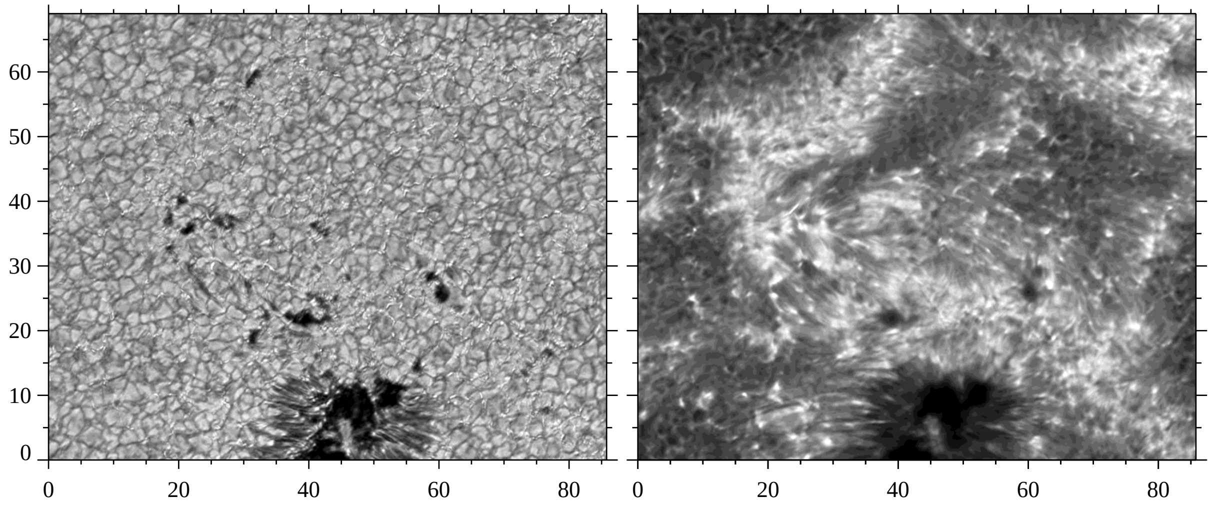


Figure 2: Sample images from a DOT tomography sequence taken on December 8, 2002. Image scales: arcsec. Left: G band image, sampling the deep photosphere. The tiny magnetic elements in the intergranular lanes (bright dots) show up thanks to the high resolution. Right: synchronously taken Ca II H image, sampling the low chromosphere about 700 km higher. The active region shows penumbral extensions and field alignments. Elsewhere, the magnetic elements combine into bright chromospheric network. The darker areas display convective overshoot and acoustic wave patterns. The seeing was only fair (cf. Fig. 7 on page 15).

the first to obtain images of $0.2''$ sharpness through frame selection during superb seeing and a pioneering 20-min image sequence at that resolution through phase-diverse restoration. The DOT (45 cm) became the first solar telescope to regularly achieve this resolution continuously over multiple hours and large fields ($80'' \times 60''$) at high cadence (30 s) thanks to its successful open principle, superb optical performance, exceptional mechanical stability, and consistent speckle reconstruction. The resulting DOT movies are world famous. They are available at `http://dot.astro.uu.nl` together with DOT publications, reports, and further details.

Of particular importance is the excellent temporal sequence homogeneity. When the La Palma seeing is good enough for speckle restoration up to the $0.2''$ diffraction limit (which occurs fairly frequently), an entire multi-hour image sequence consistently possesses nearly diffraction-limited resolution. The solar-physics emphasis on magnetic field evolution and dynamics makes such unprecedented seeing-free homogeneity essential.

The DOT project is presently funded by UU, NWO, NOVA and the EC in a three-year “science utilization” program deploying multi-channel optics and an elaborate speckle data acquisition system. Many DOT initial movies (overview in Fig. 7 on page 15) were optics and speckle system tests. The speckle acquisition system is now complete. Two optics channels (blue continuum and G band) are working; two more (Ca II H and continuum near Hα) are presently mounted. The latest movie is the first tomographic one: synchronous G band and Ca II H with unprecedented sustained sharpness of the latter (Fig. 2; cf. footnote on page 17). The final two channels will be installed later this year. They sample the Hα and Ba II 455.4 nm line profiles using high-quality tunable birefringent Lyot filters on indefinite loan from the Canadian Research Council and the Institute of Solar-Terrestrial Physics at Irkutsk.

The six synchronous channels together constitute tomographic sampling of the solar atmosphere from the deep photosphere (continua and G band) through the low chromosphere (Ca II and Ba II, the latter especially for Dopplershift) to the high chromosphere (Hα). Complementary EUV and X-ray observation from space adds coronal topology and dynamics.

DOT niche by 2005. Its multi-wavelength speckle imaging makes the DOT in principle the first-choice-worldwide tomographic imager of the magnetic fine structure, topology, and dynamics of the photosphere, low chromosphere and high chromosphere all at the same time. In practice, however, the DOT productivity is presently limited severely by the computer-intensive speckle reconstruction to only a few sequences per year (cf. Fig. 7). With all six cameras taking speckle bursts, a two-hour run needs a month of wall-clock processing time on our present 14-computer system – a ratio of 350 between observing duration and processing duration.

A successful code parallelization effort during the past years has shown that considerable speedup is possible with hybrid cluster architecture. An "apparatuur-M" proposal for an elaborate *DOT Speckle Processor* (DSP) was submitted to NWO earlier this year. The DSP will achieve overnight processing of eight-hour runs using all six cameras at 30 s cadence, two orders of magnitude improvement.

Our aim is to install the DSP the coming winter. We then become manpower-limited instead of resource-limited with respect to DOT observing. We aim to start frequent six-camera DOT observing next summer in a PI-led student-service mode. This program will consist of two-week student traineeships at the telescope including solar physics teaching by the PI (who intends to spend half a year per year on La Palma for this purpose).

With DSP pipelining and student-serviced operation, the DOT will fill its science niche no longer in "Utrecht-only" fashion – in which just one good tomographic run on an active region, plage, or even a quiet solar area is likely to contain enough material for a complete PhD thesis (as was the case with two famous SVST image sequences during the past decade, effectively the source of most SVST papers including an Utrecht thesis). Instead, we will open the DOT to the world through peer-review time allocation described below. It should start in 2004 and be fully operational in 2005. The DOT should so become the premier tomographic solar atmosphere mapper for virtually *any* high-resolution solar physics program addressing solar magnetism.

DOT^{++} niche past 2005. The DOT niche is likely to be filled in superior fashion from 2006 by the Japanese-led Solar-B satellite. Solar-B will contain a 50-cm telescope combining optical tunable-filter imaging and optical spectropolarimetry with ultraviolet diagnostics. It will yield DOT-like wide-field multi-wavelength imaging – without interruptions from bad seeing, bad weather, nights, or operational constraints. It is likely that the DOT will scoop some of the intended Solar-B "firsts", but there is no doubt that Solar-B will play the role in photospheric imaging which TRACE now fills in $1''$ coronal imaging – reliably delivering uninterrupted homogeneous-quality data streams – at $0.2''$ resolution.

Solar-B will not fully kill the DOT niche since one single telescope does not meet all science needs ("one Keck isn't enough"). For example, mapping both anchor ends of a coronal loop requires two such high-resolution imagers, and the DOT's tunable Ba II filter remains special. However, the DOT^{++} aperture tripling proposed here will fully regain the DOT's forefront niche. It will actually enhance Solar-B through co-observing: the DOT can then image at $0.07''$ (50 km on the solar surface, equal to the photon mean free path in the photosphere) what Solar-B diagnoses polarimetrically at $0.2''$.

Impact. Realization of this proposal makes The Netherlands compete at the $0.1''$ solar physics frontier with a unique Dutch facility, at low cost compared to any other solar telescope project.

Dutch context. This proposal fits renewed Dutch interest in solar astrophysics. The Utrecht FacNS decision to organize UU solar physics in a labeled program and to allocate a full chair to it demonstrates its intent to strengthen Utrecht solar physics. Present research topics in-

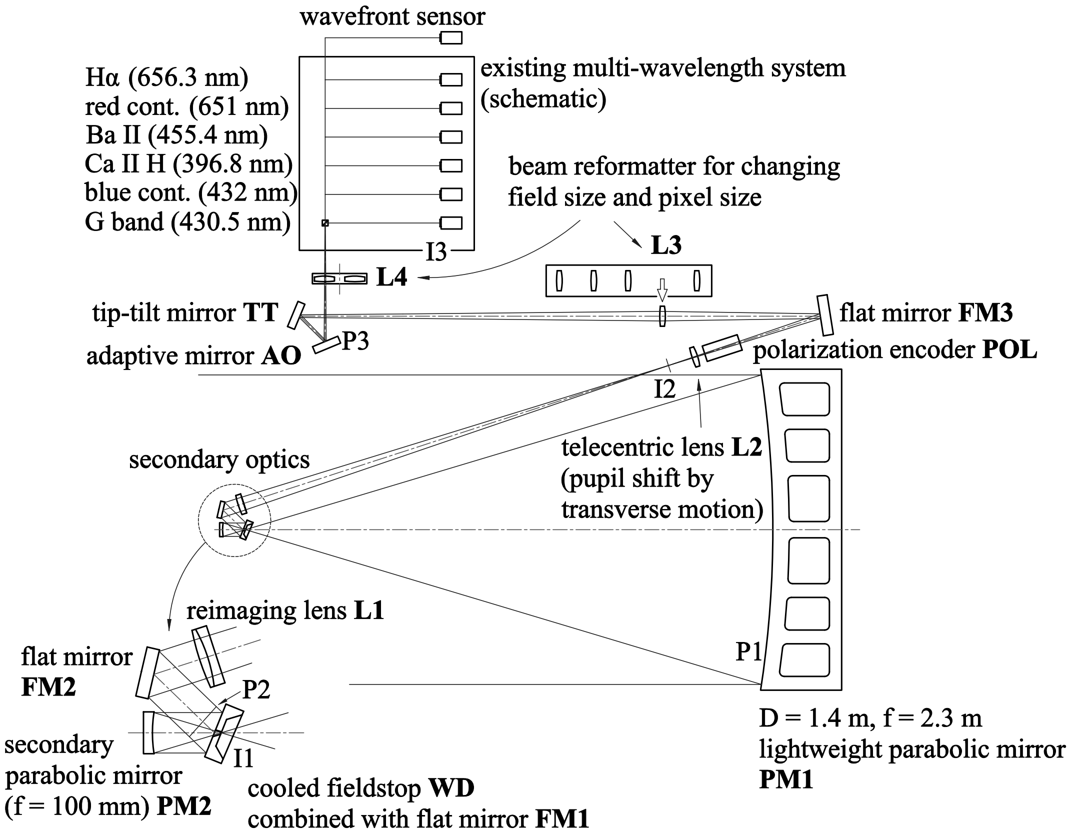


Figure 3: Optics scheme for DOT^{++}. Sunlight enters from the left. The box at the upper left denotes the present multi-wavelength system which remains the same. P1, P2, P3: pupil planes. I1, I2, I3: image planes. PM1, PM2: parabolic primary and secondary mirrors. FM1, FM2, FM3: flat folding mirrors. L1, L2, L3, L4: re-imaging and field lenses.

clude fluxtube topology and dynamics, sunspot structure and oscillations, and chromospheric waves. J.M.E. Kuijpers' move to Nijmegen implies new solar physics interest there, specifically in prominence topology, prominence eruptions, and CMEs. The plasma physics theory group at Rijnhuizen (FOM) maintains its concentration on solar plasmas with specific interest in coronal loop dynamics (J. Goedbloed, R. Keppens).

4 Instrument concept

DOT^{++} aperture upgrade. We propose to replace the present 45-cm DOT primary with a 140-cm mirror, the largest size that can be accommodated in the present telescope mount. The latter can easily support the increased weight. The present multi-channel optics and speckle acquisition systems[2] will remain intact and be remounted on a new telescope-top support structure. They will be fed at the present $f/45$ ratio by folded re-imaging and beam-reformatting optics. The latter permit user-selectable choice between angular resolution and field of view, which will vary with the observing conditions and the science goals (see below).

[2]Currently, each of the six filter channels has its own 1296×1030 px CCD camera feeding speckle frames at 10 frames/s via its own fiber link to its own dual 600 MHz PC with 72 GB storage in the Swedish building. This capacity, archived overnight on tape, limits the observing duration to 2.2 hours at 30 s speckle burst cadence. The new DSP (current NWO-M application) will store 8-hour runs and process these overnight.

A fairly detailed design has been made to verify the opto-mechanical feasibility. The central obscuration is smaller than for the present configuration in which the G-band channel is on-axis. A new highly reflective water-cooled field stop with air suction in the primary focus transmits the field of view via a parabolic secondary and flat folding mirrors to the multi-channel system. A telecentric region may harbor polarization encoders for Stokes and Hanle Ba II 455.4 nm magnetometry. A low-order adaptive-optics system (15–20 degrees of freedom) improves the speckle S/N. The beam formatter permits operational choice between resolution and field. A beam shifter provides obscuration-free off-axis aperture choice up to $D = 65$ cm.

Figure 3 gives details. The primary PM1 ($D = 140$ cm, $f = 230$ cm, $f/D = 1.64$) has the maximum dimensions that still fit the present telescope mount and clamshell canopy. The prime-focus field stop WD reflects the unused part of the solar image out of the telescope. Water cooling keeps it at ambient temperature; air suction flushes its surroundings to avoid schlieren in the incoming beam. The parabolic secondary PM2 has $D = 7$ cm, $f = 10$ cm and is confocal with PM1, giving full correction of coma and spherical aberration. The central obscuration caused by PM2 and FM2 is unusually small (15% diameter at 140-cm aperture).

For the remainder an optical train (L1 through L4) has been selected that combines operational versatility with the existing multi-wavelength camera system and has a large and well-accessible telecentric region (pupil in infinity) for a polarization encoder POL, a promising option for Hanle and Stokes polarimetry in Ba II 455.4 nm (which possesses large polarizability). The effective aperture can be changed by pairwise changing L3 and L4. Different L3 lenses, chosen from a selection box, produce different enlargements of the entrance pupil P1 on the pupil plane P3. The corresponding L4 (wheel) keeps the final image plane I3 at the multi-wavelength camera chips. The design has the unique feature that the pixel size (in arcsec on the sky) automatically scales with the diffraction limit defined by the selected effective aperture.

The design also incorporates pupil shift selection. Transverse shift of L2 shifts the P3-confined final pupil across the entrance pupil P1. This enables off-axis pupil selections devoid of central obscuration up to effective aperture $D = 65$ cm.

AO-improved speckle reconstruction. The effectiveness of solar speckle reconstruction diminishes with aperture size, so that better seeing is required to achieve complete restoration. The question is how much. Because there is no solar speckle experience beyond the 70-cm class apertures at Sacramento Peak and Izaña, we turned to computer simulation for quantitative estimation of the feasibility of speckle reconstruction at 140-cm aperture, with expert help from C.U. Keller (NSO Tucson) who investigates similar issues in ATST design. Results are shown in Fig. 4. The first conclusion is that even at 140-cm aperture, solar speckle reconstruction is a viable technique already for Fried parameter $r_0 = 10$ cm ($\alpha = 0.07$). The second conclusion is that adding low-order adaptive optics (AO) is highly desirable, as indeed strongly advocated by Keller and independently by solar speckle expert O. von der Lühe (KIS Freiburg) in order to gain speckle S/N. Speckle reconstruction is to first order independent of the telescope diameter for point sources (or not too complex collections of point sources) because the flux gain cancels against a factor r_0^2/D^2 in the speckle transfer function, but extended objects such as the solar surface have lower power at larger spatial frequencies, implying lower speckle S/N and reconstruction efficacy at larger aperture. Low-order AO regains much speckle S/N; the test shows that it improves the speckle reconstruction substantially.

In general, AO wavefront correction, phase-diverse (PD) image restoration and speckle reconstruction (SR) are complementary techniques, respectively operating in the pupil plane, the focal volume, and the image plane. Combination is desirable and actively pursued at the NSO

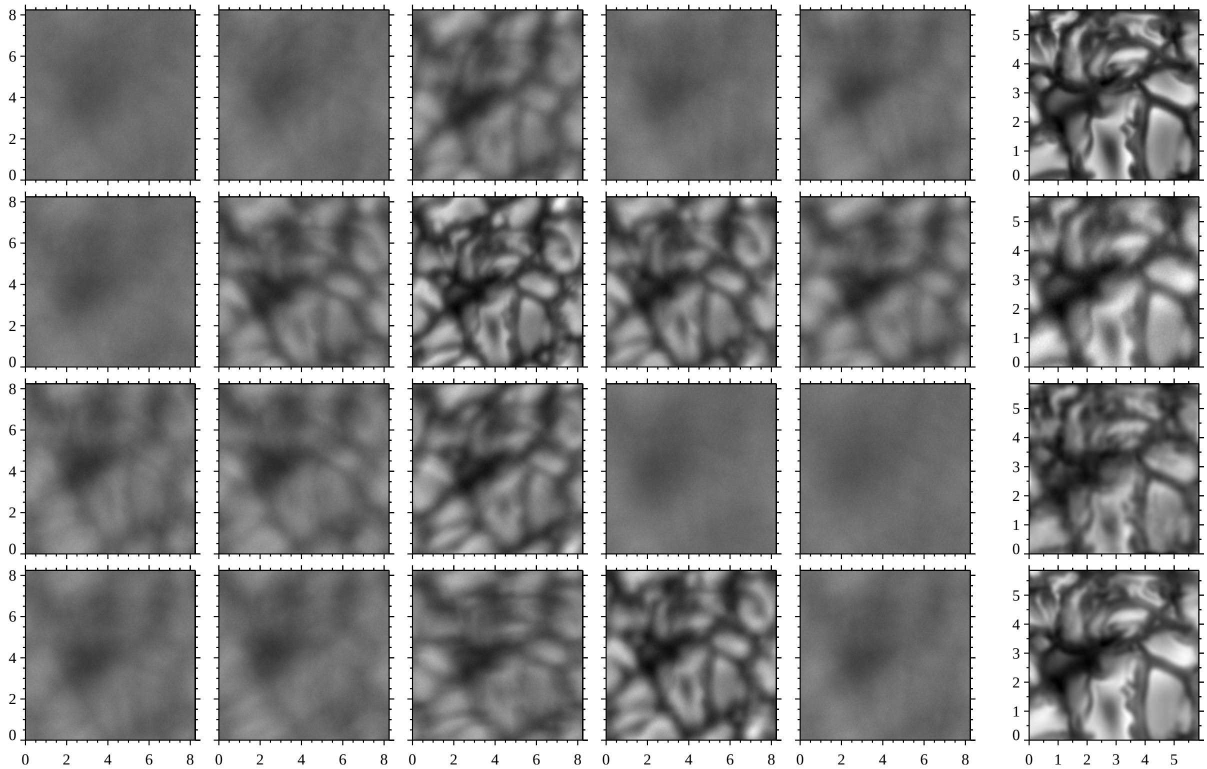


Figure 4: Speckle simulation. The scales are in arcsec. The 20 frames at left are every 10th from a computer-generated 200-frame burst "observed" with 140 cm aperture during r_0 = 10 cm seeing. The four panels at right are the original solar scene, the best frame (which happens to be the 8th at left, at different scales), the result of speckle reconstruction using the full burst, and the result of speckle reconstruction combined with low-order adaptive optics (AO). The unspoiled ("perfect") scene comes from a convection simulation by Nordlund & Stein which closely matches solar granulation, has appropriate numerical resolution (24 km cell size), and contains sufficient spatial detail at scales corresponding to the 0.07″ diffraction limit of a 140 cm telescope even though the simulation does not contain magnetism (which produces high-wavenumber features in intergranular lanes, cf. Fig. 2). The seeing-spoiled sequence was generated by C.U. Keller using a suite of programs developed for comparable methodology tests for the 4-meter ATST. His codes apply a pupil phase screen with a Kolmogorov spectrum, in this case with r_0 = 10 cm. Shot noise was added corresponding to the well depth of the DOT cameras. The images at right cover a smaller area because the seeing caused substantial image motion and corresponding border removal in the speckle reconstruction. The third image on the right results from feeding the simulation to the DOT speckle code. The fourth image is a similar reconstruction of a similar simulation but applying a low-order AO (37 actuators) system. The images show, respectively, that at 140-cm aperture and 10-cm seeing, speckle reconstruction delivers a much better result than frame selection, and that low-order AO enhances speckle reconstruction to nearly diffraction-limited imaging.

Dunn Solar Telescope, the SST, the German telescopes at Izaña, and BBSO. The PD and SR post-processing serves usually to increase the restored field size over the central isoplanatic patch optimally corrected by high-order AO. In contrast, the present 45-cm DOT reaches nearly diffraction-limited resolution with SR alone already at 7 cm seeing over its whole field of many isoplanatic patches. Since DOT^{++} will also be used exclusively for sequence imaging, not for spectrometry, it is logical to apply AO-improved large-field speckle reconstruction as DOT^{++} workhorse technique.

Low-order adaptive optics. Adding low-order adaptive optics will mostly require effort but no system development since the technology is maturing now and will be well-established by 2005. Keller's relatively cheap system for the McMath-Pierce telescope is a good example. The DOT^{++} system will use pupil P3.

Resolution versus field flexibility. At times when the seeing does not reach $r_0 \approx 10$ cm (cf. Fig. 7), the $0.025''$/px image scale appropriate to $0.07''$ resolution represents wasteful oversampling which unnecessarily limits the actual field of view set by the camera chip sizes. Hence the addition of the beam reformatting optics which permit trading field against resolution, with larger field preferable during less good seeing. For example, 4K×4K chips will register $300'' \times 300''$ at $0.2''$ resolution, over four times the maximum Solar-B field of view, and so enable studies of the topology and dynamics of whole active regions including complete coronal loop anchoring. Large-field preference may also be dictated by observing programs desiring to catch a flare or a prominence eruption. When the seeing turns excellent – as flagged by our indicative Beckers-Seykora scintillometer – quick shift to $0.07''$ resolution then reduces the field to $100'' \times 100''$, still large enough to contain a complete mature sunspot with its full moat.

DOT^{++} speckle pipeline upgrade. The second part of this proposal is to retro-fit the DOT cameras and speckle processor by 2008 with state-of-the-art hardware in order to triple the DOT field of view at any resolution. By that time, the cameras and DSP will be quite outdated – if not obsolete. Much larger CCD chips with the 10 frames/s readout speed needed for speckle burst registration should become affordable; computer disks and processors are likely to keep advancing at about the pace of Moore's law. The aim is to install 4K×4K cameras and to increase the DSP speed by one order of magnitude, so that overnight processing of large-field 8-hour 6-camera runs remains viable.

This part of the proposal is limited by off-the-shelf hardware advance and does not require detailed design at this stage. The DOT^{++} speckle processor will probably emulate the hybrid architecture of the currently NWO-proposed DSP. The latter has a master computer with large disk capacity handing out the pre-processing and post-processing to five large-memory computers, which each divide speckle reconstruction over 20 small-memory diskless CPU's (detail under Documents on the DOT website).

5 Technology availability

Primary mirror. The primary should be lightweight and of hollow construction to avoid heat collection.

Since the mirror is the most expensive and uncertain cost item, further study as well as scrutiny of developments elsewhere are needed for the selection of the mirror material and vendor. The material choice is between:

- SiC. Very large thermal conductivity, 60 times higher than Zerodur. Worse thermal expansion. Very light, sufficiently stiff per unit weight to be self-bearing. Very brittle. New material, with a lack of experience. There are SiC mirrors in production for GREGOR and ESA. Cost estimate: k€ 250–400.
- Ceramic (Zerodur, Cervit, ULE). Lowest thermal expansion. Well-proven technology. Cost estimate: k€ 150.
- Borosilicate (Pyrex). Inexpensive, but too unstable against temperature variations. Cost estimate: k€ 80.

It seems wise to wait another year for SiC validation. SiC seems the first DOT^{++} choice, but Zerodur remains a viable backup.

Mirror support. The present DOT mirror support is an intricate self-balancing friction-free device supporting the heavy 1:6 primary in any orientation without radial or azimuthal stresses.

The aim for DOT^{++} is to obtain a lightweight mirror of sufficient stiffness to be mounted in much simpler fashion.

Heat stop. The cooled field stop WD is very close to flat mirror FM1 and must be integrated with it. The heat load on the DOT^{++} field stop, to be removed by water cooling through a labyrinth maze close to the reflective surface, will be eight times the load in the current DOT. It necessitates higher reflectance (silver plus hybrid multi-layer coating), increased water flow, and a substantially larger cooling surface. A porous sinter material seems best, with SiC the prime candidate. Experiments and prototype performance tests will be necessary to settle the final design.

Telescope top. The steel framework supporting the secondary optics, from the declination axis upwards, must be renewed for DOT^{++} while the multi-wavelength system remains intact. The bearings and drives can also remain since the 16-ton telescope is sufficiently stiff to support a tripled mirror without mechanical performance degradation (precision tracking in strong wind buffeting). The multi-wavelength system will again be located in the telescope top (but without an on-axis central tube, as the G-band channel in the present DOT). The major design requirement is stiffness against vibration, since bending from slower thermal expansion/contraction will be actively compensated by PM2 positioning. The current DOT top is vibrationally stiff to within 1 μm; the DOT^{++} top must reach the same value.

The larger parts will be welded rather than bolted together to save construction time, and the assembly will be done in the Netherlands (easy relocation was an original DOT design desire which we no longer maintain – being happy with La Palma). Replacing the old with the new top will be a matter of just weeks, with minimal DOT out-of-service duration.

6 International context

The DOT research is embedded in the Utrecht-coordinated 11-institute EC/RTN *European Solar Magnetism Network* (ESMN). There are very close ties to the solar groups at Stockholm (RSAS) and Oslo (ITA), and on-going collaborations with solar groups at Freiburg (KIS), Palo Alto (LMSAL), Boulder (HAO), Bozeman (MSU), Sunspot (NSO), and Kiev (MAO).

The DOT engineers are technically involved in most solar telescope projects aiming at the $0.1''$ barrier relying on adaptive optics. The first to reach it is the new Swedish 1-m Solar Telescope (SST), a 96-cm aperture vacuum refractor which recently replaced the 48-cm SVST. The DOT team contributed the guider as well as parts of the turret design and supervision of its construction. The initial SST adaptive-optics imagery demonstrates a new vista of solar atmospheric structure and dynamics at $0.1''$, proving that high resolution is essential in studying solar activity. The SST is now the sharpest solar telescope and will remain that for some years. The DOT, operated from the SST building in close Swedish-Dutch collaboration, will often co-observe in tandem.

The next relevant project is the German GREGOR retrofit of an old telescope on Tenerife into an open 1.5-m reflector, inspired by the DOT and copying the DOT canopy including assembly in Delft. Operation is likely by 2006.

In the proposal stage are the 1.6 m New Solar Telescope for Big Bear Solar Observatory and the 1 meter Indian MAST for Udaipur Solar Observatory.

The flagship project in groundbased solar physics is the US Advanced Technology Solar Telescope

(ATST), a 90 M$ project aiming to put an open 4-m telescope, also DOT-inspired, at a superior site (La Palma being tested as candidate). The principal aperture driver is photon flux for precision polarimetry at about $0.1''$ resolution. First light perhaps by 2010. There is an initiative underway for European partnership in EC-FP6 context, with Utrecht a partner[3].

These new adaptive-optics telescopes mainly target Stokes magnetometry with Fabry-Perot filtergraphs and grating spectrometers. DOT^{++} wide-field multi-wavelength tomography remains highly complementary.

In space, the major advent will be the launch of Solar-B, discussed in Sect. 3 above. NASA's large *Solar Dynamics Observatory* (SDO), effectively the successor to both SOHO and TRACE to be launched in 2007, will use many 4K×4K detectors for continuous simultaneous high-cadence full-disk imaging in Stokes V, Doppler and many EUV wavelengths with $1''$ resolution, furnishing whole disk and coronal complementarity (continuously at 150 Mb/s!) to groundbased high-resolution telescopes. Combination of imaging and spectropolarimetry at the latter with SDO's comprehensiveness is likely to revamp solar physics.

NASA's recent announcement of a 2007 SMEX launch opportunity has at least two US teams proposing 0.1–$0.2''$ ultraviolet missions. The DOT group partners in both. The same holds for the German-led *Sunrise* proposal aiming at balloon-borne spectropolarimetry with 1-m aperture.

7 Observing time and access

From 2005 onwards the DOT should be open to the international community through peer-review time allocation, in PI-led student-service mode during the summer and in negotiable common-user mode at other times.

The emphasis in DOT scheduling will almost automatically lie on partnership in multi-telescope campaigns, since these have become the major and most productive observing mode in solar physics. Typically, wide-field DOT speckle tomography will be combined with SST adaptive-optics observing, infrared spectropolarimetry with the other European telescopes on Tenerife, and space observation (SOHO, TRACE, and RHESSI now; Solar-B, SDO, and others in future).

Note that such partnerships do not imply that DOT time is "given away" to non-contributing outsiders. In modern solar physics, observing has become a community-wide effort, sharing facilities and data with access to all (TRACE and SDO officially, SOHO and Solar-B in practice). Keeping the DOT exclusively Dutch would restrict DOT science to our own modest manpower-limited needs, whereas opening the DOT in an open-data policy and to frequent international campaigning will make the DOT fill its niche to worldwide capacity and greatly enhance its visibility. This approach will be maintained for DOT^{++}.

It is also important to note that the fact that multi-week solar observing campaigns often produce just one key data set is less wasteful then it may appear to nighttime astronomers. As mentioned above, most SVST papers in the past decade came from one long frame-selected sequence (Fig. 8) and one shorter PD-restored sequence. Not only terrestrial seeing limits the take; for many topics, solar activity has to produce the desired behavior at the right place at the right time. Although, from 2007 onward, SDO will continuously monitor active phenomena full-disk at $1''$ resolution, Solar-B will measure only much smaller areas at $0.2''$ and visible-wavelength lower-atmosphere measurement beyond Solar-B's resolution will remain the realm

[3]The Utrecht group is also involved in an MPI Lindau-led FP6 proposal to develop advanced multi-layer liquid-crystal technology for spectropolarimetry, possibly enabling future application at the DOT.

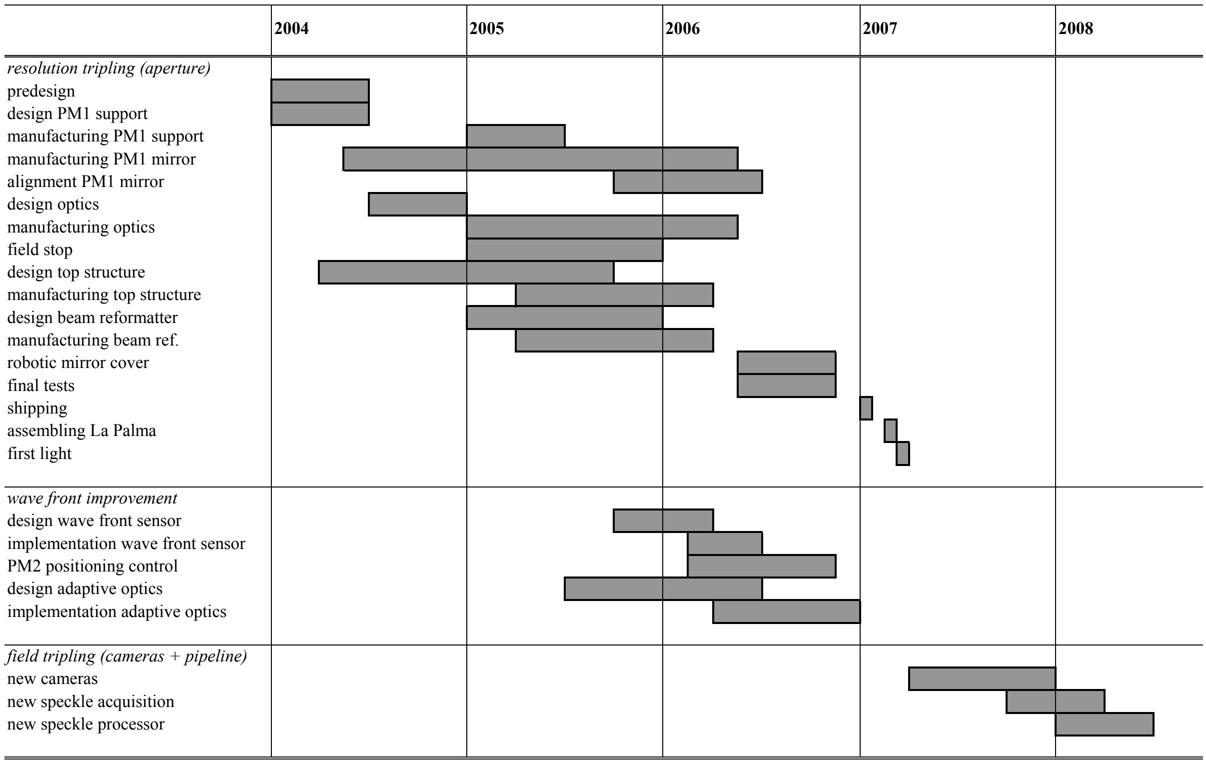


Figure 5: DOT^{++} realization time schedule.

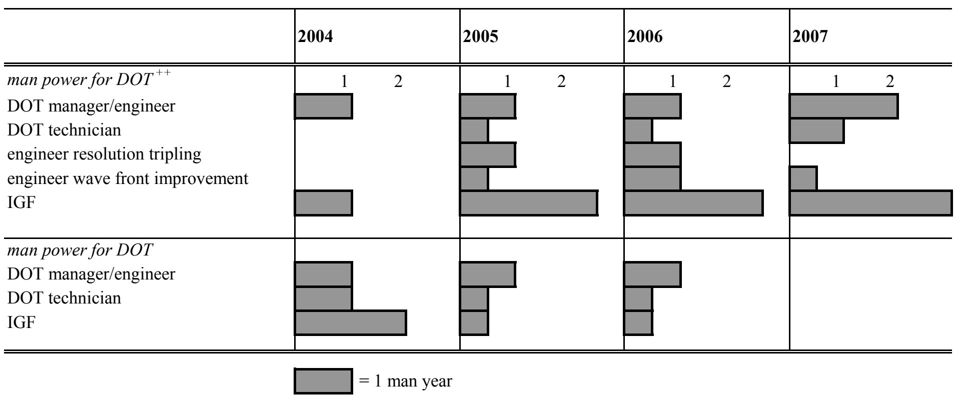


Figure 6: DOT^{++} manpower distribution. The DOT manpower before DOT^{++} first light concerns ongoing DOT science exploitation.

of groundbased observing, unavoidably with intermittent sampling and event "hunting".

The DOT^{++} strategy is to make the DOT a major player in $0.1''$ solar physics. The longer-term strategy is to make the DOT an integral part of the upcoming Virtual Solar Observatory (see *"White paper on future DOT observing modes"* under Documents on the DOT website). The plan does not foresee remote operation which is too risky, but it does include web-based remote targeting which is relatively easy to implement even at low communication bandwidth.

8 Management plan

Bettonvil is envisaged as DOT^{++} project manager. His track record in on-time delivery of the DOT projects that he supervised so far is excellent (*e.g.,* the high-quality phase-diverse video autofocus system). DOT^{++} progress reporting will adhere to the NOVA/ISC rules.

Figures 5 and 6 specify the project time schedule and manpower distribution.

The basic opto-mechanical designs will be done by Hammerschlag and Bettonvil. Completion of the multi-channel imaging system will free them for this effort by 2004. Much outsourcing of detailed design verification, optics component tests, quality control, and small-component fabrication to optics companies and to ASTRON is foreseen. It is included in the budget (Table 1 on page 17). The budget also specifies two contract engineers (with different degrees and experience levels).

Selecting, ordering, manufacturing, figuring and polishing the primary mirror is the slowest component and must start already in 2004 in order to reach delivery medio 2006. The design of the mirror support and alignment hardware are closely related and must take place simultaneously. The mirror and support design will include finite-element modeling at TUD. The alignment hardware, which must reproducibly identify the exact location of the coma-free focus, must be tested and set at the polisher.

The timeline entry for defining, manufacture, testing, and selecting the remaining DOT^{++} optics is based on the extensive experience gained in the realization of the multi-wavelength system. The temporary engineer listed in Table 1 will be supervised by Bettonvil. Manufacture will be by industry, but testing and polishing are likely to involve ASTRON.

The water-cooled prime-focus field stop and integrated backside mirror needs technology development including prototype testing. Design by IGF (FacNS workshop), manufacture at industry, supervision by Bettonvil.

The new telescope top will be a relatively simple mechanical structure, since most complexity lies in the already existing multi-channel system. Exceptional stiffness is required, a Hammerschlag specialty. Design by him and the temporary engineer. Construction at the Utrecht (IGF) and Delft (DTO) workshops with specialist tasks performed by industry. Assembly, alignment and testing at Utrecht, Delft or Dwingeloo.

The mechanical mounts and electronic control of the secondary mounts including beam-reformatter lens choices and pupil shifter will be done by IGF, to be completed in 2006 at the same time as the primary mirror.

The realization of the active control of the secondary and low-order adaptive optics system also require an extra contract engineer.

Installation of the complete DOT^{++} top and control systems is scheduled to take place in 2007.

The subsequent renewal of the speckle system will most likely entail straightforward hardware procurement. As always in buying computer equipment, it is best to wait to the last moment before settling the choice. Expert advice will come from UU (Dr. Ir. A. van der Steen), ASTRON, and elsewhere. Adaptation of the camera control requires effort by IGF. The speckle processor assembly can probably be outsourced.

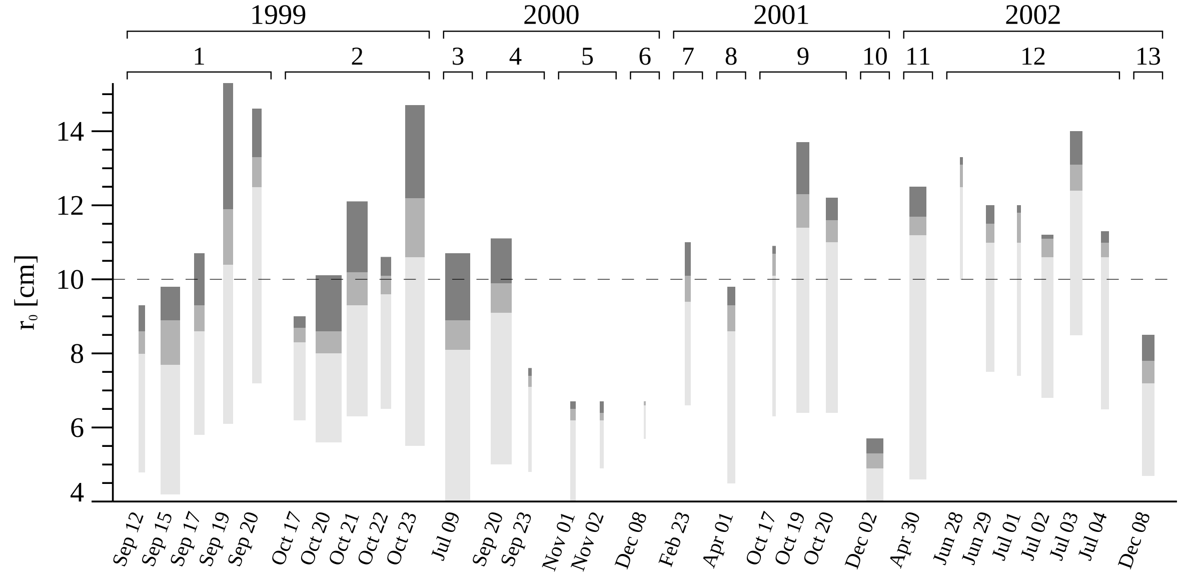


Figure 7: Seeing during the thirteen DOT observing campaigns so far. They typically lasted two weeks but with only a few days devoted to science observing. Each bar represents a fully processed speckle sequence, providing quantitative r_0 estimates per speckle burst. The bar tops specify r_0 for the best burst, the contrast changes to intermediate grey show the mean value for the best 10% bursts, the next contrast changes the mean of the best 30%. The bar bottoms show the worst value, but this is not significant when runs were continued into bad seeing. The bar widths show the sequence durations; the longest (October 20, 1999) lasted 200 min. Conclusions: (i) – the DOT has been exploited only infrequently so far (the speckle processing turnaround being a severe limitation); (ii) – although many campaigns were outside the best-seeing season, good sequences where obtained in nearly all campaigns; (iii) – restriction to $r_0 > 10$ cm during 1/3 of the time passes 1/3 of these sequences, with a good chance of getting at least one per campaign.

9 Deliverables and milestones

The timeline diagram in Fig. 5 and the descriptions above define the following milestones:

- 2003: speckle tests without and with AO at the SST;
- 2004: start high-volume observing (multi-wavelength registration and overnight speckle processing in place, initial student-serviced time allocation);
- 2005: complete DOT niche filling, completion of DOT^{++} optics design, selection of mirror manufacturer and polisher, field-stop prototype tests, start of DOT^{++} top construction;
- 2006: completion of the aperture upgrade, active and AO wavefront sensing and correction, final DOT^{++} top assembly;
- 2007: installation on the DOT, start of 0.07$''$ observing; definition and procurement of new cameras and speckle processing hardware;
- 2008: full wide-field DOT^{++} operation; start of remote targeting; integration into VSO.

10 Risk analyses

Optics alignment. The parabolic primary M1 and secondary M2 must be aligned accurately to avoid coma. The radial alignment is 20 times more critical than in the current DOT and

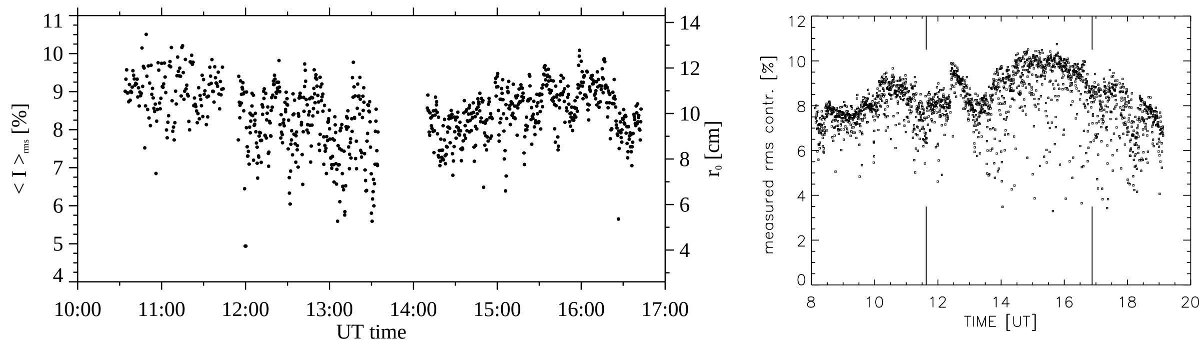


Figure 8: Diurnal seeing variation. Left: DOT, September 20, 1999. Three runs were taken with the initial DOT video camera. The first, until 11:45, was speckle-reconstructed into a famous sunspot movie which became the first solar movie on "The Astronomy Picture of the Day" (http://antwrp.gsfc.nasa.gov/apod/ap000223.html). The other two sequences resulted from video frame selection. For these the rms intensity contrast of the solar granulation was converted into r_0 using the first sequence as calibration. Right: famous 11-hour Brandt–Simon sequence taken on June 7, 1993 with the SVST using digital frame selection. The granulation contrast scales are not directly comparable because the wavelengths and straylight pedestals differ.

requires precision to within 5 μm. The DOT mirror was interferometrically measured in an UU lab to identify the coma-free focus position. A mechanical alignment cone and a laser pointer were then constructed for the final telescope alignment. DOT^{++} alignment requires similar measures, preferably in close collaboration with the manufacturer. In addition, slow active-optics correction with low-order wavefront sensing is required. Mirror M2 will be mounted on an X/Y stage; the wavefront sensor along the multi-wavelength system (Fig. 3).

The axial Z adjustment will be regulated with the present DOT focus slide and well-proven phase-diverse autofocus system. The latter will be even more necessary than it is now, due to larger sensitivity to thermal telescope top expansion and contraction.

Seeing quality. Figure 4 suggests that 10-cm seeing suffices to obtain near-diffraction-limited resolution at 140-cm aperture with AO-improved speckle reconstruction. There is no way in which this prediction can be tested with a real telescope on the real sun. However, the SST permits such tests at virtually the DOT site for 96-cm aperture (a test with THEMIS at 90-cm aperture was inconclusive due to poor optics). Our intent is to test both straightforward and AO-improved speckle reconstruction at the SST using DOT cameras later this year, in collaboration with the Swedish team using International Time allocation.

Seeing frequency. There is no hard material about day-time seeing statistics at the DOT site to reliably estimate how often 10-cm seeing occurs. The very intensive test campaigns through which the Canary Islands were originally established as superior solar sites (Brandt & Woehl, A&A 109, 77, 1982; Brandt & Righini, Vistas in Astron. 28, 437, 1985) were inconclusive with respect to telescopic r_0 measurements because the La Palma test telescope was badly sited (at the Roque de los Muchachos summit itself, on top of the solar-heated slope facing the morning sun). The Swedish SVST nor the DOT scintillometer have yielded long-duration records. The general conclusion from 15 years of SVST experience is that two-week campaigns tend to hit excellent seeing at least some days during the mid-May – mid-October season, and that superb seeing can occur at any time, also mid-winter. The ATST site-test program will improve the statistics the coming years.

Figure 7 displays the complete DOT record as derived from speckle reconstructions, which

project part	salaries	procurement	totals
resolution tripling (aperture)	k€	k€	k€
engineer (experienced Ing., 2 yr)	105		
development and tests (SIU, ASTRON)		50	
primary blank (TBD)		150 – 400	
primary polishing (TBD)		200	
primary mirror support (SIU, IGF)		40	
tests and alignment hardware (SIU, ASTRON)		40	
cooled field stop and secondary (TBD)		50	
beam reformatter optics (WZW, ASTRON)		90	
telescope top (SIU, IGF)		70	
assembly and alignment (SIU, ASTRON)		50	
robotic mirror cover (SIU, IGF)		10	
transport and installation		40	895 – 1 145
wavefront improvement (active + adaptive optics)			
engineer (starting Ir./Drs., 2 yr)	95		
secondary positioning control (*e.g.,* Molenaar)		40	
wavefront sensor (Okotech)		10	
low-order AO system		50	195
field tripling (speckle cameras + pipeline)			
6 4K×4K 10 fps CCD cameras		120	
6 image-acquisition computers		120	
overnight speckle processor		200	440
grand totals	200	1 330 – 1 580	1 530 – 1 780

Table 1: DOT^{++} cost specification. The first group specifies the aperture tripling from 45-cm to 140-cm telescope diameter which triples the diffraction-limited resolution to 0.07″. The choice of primary mirror material between SiC and Zerodur represents the major uncertainty. The second group concerns slow secondary position control and low-order adaptive wavefront correction, serving to substantially increase the fraction of the time that 0.07″ resolution is actually reached. The third group concerns renewal of the speckle cameras and processor, yielding three times larger field of view at any resolution. The procurement costs include outsourcing. The IGF entries concern materials only, assuming IGF effort to be an in-kind FacNS contribution.

deliver a reliable r_0 evaluation from each speckle burst. There have been thirteen campaigns so far. Most combined technical development with partial observing, the latter often serving to test optics concepts and solutions for the multi-wavelength system. The seeing-quality pattern[4]

[4]Three examples: the October 17, 2001 sequence was the first two-channel one, combining G-band and nearby continuum. It is analyzed in an ApJ paper in press (Nisenson, van Ballegooijen, de Wijn & Sütterlin). The December 2, 2001 run was part of a THEMIS campaign. Despite the bad seeing, the DOT images were of sufficient quality to identify solar features not visible in the lower-resolution THEMIS spectra. The December 8, 2002 sequence is the very first tomographic one, combining synchronous G-band and Ca II H. It targeted a quiet area. The seeing was meager but the Ca II H sequence quality is unprecedented. A quote from a recent email between US colleagues: *"The December 2002 DOT dataset is ideal, both in terms of field-of-view and consistency of resolution, for our analysis of quiet Sun acoustic wave studies. The quality of this dataset is as high as anything I've ever seen from a 1/2-meter class solar telescope. I recommend that we use this dataset for our next analyis rather than the one we are currently reducing."* The images in Fig. 2 of a more active region were taken the same day but the sequence processing is yet incomplete.

confirms the SVST experience. From 2004 onward the DOT sampling will improve dramatically through much more frequent observing, permitted by DSP overnight processing and the student program.

Figure 8 illustrates an important La Palma characteristic: good day-time seeing may last all day. This property distinguishes the Roque de los Muchachos favorably from most other mountain sites, where solar ground heating usually spoils the seeing soon after sunrise. The DOT is particularly suited to long-duration sequencing because its parallactic mount does not impose diurnal image rotation.

11 NOVA and other funding

Table 1 specifies initial cost estimates for both DOT^{++} upgrades. These mostly concern hardware, apart from the listed two contract engineers and outsourcing contained in the procurement costs.

As described in Sect. 2, increased UU solar physics manpower and continuation of the DOT team in at least its present capacity are assumed, as well as continued funding for DOT exploitation. The budget also assumes continued allocation of generous amounts of IGF workshop time as FacNS in-kind contribution. Thus, a large UU contribution is budgeted implicitly. In addition, the DOT team will maintain its efforts – so far successful – to attract other funding (presently NWO, EC/RTN, INTAS, SOZOU, and smaller grants).

The "field tripling" represented by the second + in DOT^{++} and by the third group of entries in Table 1 is independent of and extra to the "resolution tripling" itemized in the first group. The second group, "wavefront improvement" is not independent of the first because the low-frequency PM2 control needs the wavefront sensor. It is a matter of policy to bundle or not bundle the three item groups. Obviously, all three are desired scientifically.

12 Educational aspects and impact

The Dutch ownership of the DOT permits unusually large student participation. In the past the DOT realization and installation involved dozens of technical trainees, many coming to La Palma.

The planned student-service program targets ten two-week stints per year by pairs of Dutch astronomy students. They will gain hands-on experience with state-of-the-art instrumentation, observing, data acquisition and reduction techniques in international campaigns at the major astronomical observatory in Europe. They will also get an on-site solar astrophysics course from the PI, exploiting the excellent SST solar physics library and likely involving guest-teaching by foreign DOT and SST observers on bad-seeing days. The program constitutes an exciting astronomy education opportunity.

Longer traineeships will also be possible, likely on EC funding. DOT^{++} realization will again involve technical traineeships and permit technical-physics graduation research.