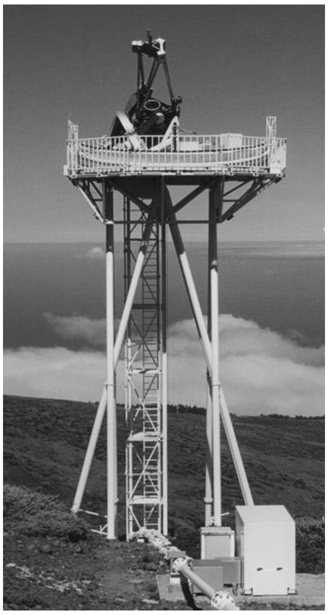
Dutch Open Telescope
&
Virtual Solar Observatory

White paper on future DOT observing modes



The Dutch Open Telescope (DOT) on La Palma is a revolutionary optical telescope for high-resolution tomography of the solar atmosphere. It combines a pioneering design with superb multi-wavelength optics and consistent image restoration through speckle reconstruction.

This document describes the steps needed to make the DOT a key component of the future world-wide Virtual Solar Observatory. Data compression through fast on-site parallel speckle reconstruction will enormously increase the DOT image production and will permit generous allocation of DOT observing time to the international community, with DOT operation contributed through a valuable student traineeship program. Remote targeting will assist flexible participation in multi-telescope campaigns. Combination of the resulting data base with high-speed access will constitute a premier high-resolution resource in worldwide solar physics.

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The Dutch Open Telescope on La Palma. The 45 cm parabolic primary mirror is seen near the center of the photograph. The slender tube at the top contains a water-cooled prime-focus field stop, re-imaging optics and a digital CCD camera. Four more cameras are being mounted with elaborate filter optics on the heavy support struts besides the incoming beam. The images are transported through optical fibers to the nearby Swedish telescope building. The DOT is open and is mounted on a 15 m high open tower to exploit the superior atmospheric seeing at La Palma brought by the oceanic trade wind. The clamshell bad-weather canopy is folded away in this view.

Executive summary

The Dutch Open Telescope (DOT) is an innovative solar telescope on the Canary Island La Palma. It successfully aims at tomographic high-resolution imaging of the solar photosphere and chromosphere.

The initial DOT science validation phase is presently completed and has been peer-reviewed with highly positive outcome. A science exploitation phase is starting in which the DOT will be used for sustained multiple-wavelength imaging of the solar atmosphere at unprecedented angular resolution.

The present image processing hardware at the DOT limits its high-resolution data gathering capacity to only a few yearly observing campaigns. Such limited use may suffice to feed the solar physics research by the small DOT group at Utrecht, but very much underexploits the unique capability which the DOT offers to world-wide solar physics.

This document describes the steps needed to turn the DOT into the productive large-pipeline and remotely-targetable imager that its superior quality warrants. They will enable the DOT to earn premier rank in the up-coming worldwide Virtual Solar Observatory. They are:

(a) – *achieve hundred-fold data compression at the telescope by accelerating the on-site speckle processing to overnight turnaround;*

(b) – *turn the DOT into a common user facility;*

(c) – *implement user interfaces for remote targeting via the web;*

(d) – *install the server capacity needed to make the DOT an integral part of the Virtual Solar Observatory;*

(e) – *increase the bandwidth to La Palma sufficiently to enable fast image retrieval from abroad.*

The first step is the major one. It can be taken now through funding parallelization of the speckle processing. The next three steps require relatively small investments. The last step should be taken in European context through the 6th EC Framework Programme.

This program of development will successively turn the DOT from a Utrecht-only facility into an international common-user telescope, remote-targeting telescope, and virtual telescope. The necessary increase in on-site manpower for operation and processing may be achieved in summer through a DOT traineeship program bringing over two dozen students a year to La Palma.

1 The Dutch Open Telescope

Introduction. The DOT is, as its name indicates, an "open" telescope. The concept is revolutionary in solar physics in which all high-resolution telescopes so far are closed and rely on telescope evacuation to avoid internal turbulence caused by internal solar heating. The DOT solves this problem instead by relying on telescope flushing by the strong trade winds which make La Palma a world-class site in terms of low atmospheric turbulence ("seeing"). The DOT's success has opened a new frontier in solar-telescope building, leading to a wave of new large-telescope projects elsewhere (details below).

In this document we describe the steps to turn the DOT itself from being just an example to others and a small-scale research asset for ourselves into a common-user facility that should earn a highly prominent position in world-wide solar physics.

Information. The DOT website (http://dot.astro.uu.nl) furnishes background information including links to the DOT database, all movies for which speckle processing is complete, photographs, the DOT publications and documents, and links to pertinent other websites (e.g., ESMN, SOHO, TRACE, NSST, GREGOR, ATST).

Status. The DOT was designed and built by Dr. Ir. R.H. Hammerschlag of the Sterrekundig Instituut Utrecht with coworkers at Utrecht and the university workshops at Delft and Utrecht. The DOT is operated from the building of the nearby Swedish solar telescope on La Palma. The first-light ceremony (by Prins Willem-Alexander) took place in late 1997. Since then, the DOT has been equipped with elaborate imaging and image registration systems in a three-year "DOT science validation phase". Funding for a "DOT science exploitation" phase the coming three years is nearly complete (NWO/E, NOVA[1], UU, EC-TMR, and private foundations).

The DOT is now widely acclaimed as the sharpest solar imager worldwide. Its unparalleled angular resolution results from the combination of low solar-induced turbulence at La Palma (confined to a thin layer by the strong trade winds sweeping the Caldera rim, with minimal disturbance from the open tower placing the telescope above it), the inhibition of internal turbulence by open-telescope wind flushing, the excellent DOT optics, and the consistent application of speckle reconstruction to correct image degradation by the remaining atmospheric seeing.

A large-volume (up to 360 GByte/day) speckle acquisition system has been installed at La Palma the past year. Extension of the secondary optics from single-beam imaging to synchronous multi-wavelength registration using five digital cameras is underway. The second camera will be mounted this autumn on a new instrumentation platform in the telescope top, the others in 2002.

Science niche. The new imaging system together with the superior image quality make the DOT fill a solar physics frontline niche consisting of diffraction-limited multi-layer tomography of solar magnetic topology and dynamics over long durations. Such tomographic imaging is highly desirable for many solar physics research programs, especially in concert with space-based ultraviolet imaging, at present with the SOHO[2] (ESA/NASA) and

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[1] NOVA: Nederlandse Onderzoekschool voor Astronomie, the highest-ranked Toponderzoekschool.

[2] SOHO: Solar and Heliospheric Observatory, first cornerstone of the ESA science programme and the flagship of current solar physics. In addition to UV imagers and spectrographs, SOHO contains the

TRACE[3] (NASA) missions, in future with the HESSI (NASA), Solar-B (ISAS/NASA), Solar Dynamics Observer (NASA) and Solar Orbiter (ESA) missions. Such tomographic imaging also remains a viable niche while the neighbouring NSST[4] becomes operational and when, towards the end of the decade, the larger GREGOR[5] and ATST[6] that are currently proposed – following DOT's demonstration of the open principle – have been completed. These new telescopes will be most effective in (spectro-)polarimetry since they will rely on adaptive optics (more below) and will therefore be complementary to the DOT wide-field imaging rather than compete, making concerted multi-telescope campaigns[7] a desirable strategy.

Evaluation. The DOT efforts and the DOT science capabilities have been peer-reviewed in March 2001 by a high-level DOT Evaluation Committee (DEC), consisting of the directors of the two principal solar physics institutes in the world and the director of the large night-time observatory on La Palma. Their very favourable report is available under "documents" on the DOT website. In a nutshell, it confirms the uniqueness of the DOT science niche, urges vigorous DOT science exploitation, and advises to seek funding to accelerate the DOT speckle processing in order to increase the DOT image output and accessibility for the larger community.

The present document takes up the last recommendation.

2 DOT science

Solar magnetism. Achieving high angular resolution over long duration in tomographic diagnostics is a principal quest of solar astrophysics. The solar magnetic field breaks through the solar surface in a hierarchy of kilo-Gauss elements ranging from sunspots

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visible-light coronograph LASCO and Michelson interferometer MDI which provide context in the form of outer-corona movies (LASCO) and photospheric Dopplergrams and magnetograms (MDI), the latter at up to 1 arcsec resolution.

[3] TRACE: Transition Region and Coronal Explorer, NASA SMEX satellite which provides solar image sequences at UV and EUV wavelengths and 1 arcsec resolution since April 1998. In particular, the Fe IX/Fe X doublet at 171 Å which samples 1 million K gas in the corona yields spectacular movies of the shape and dynamics of finely structured coronal loops.

[4] NSST: New Swedish Solar Telescope, upgrade of the former SVST (Swedish Vacuum Solar Telescope) on La Palma, from 48 cm to 96 cm diameter objective lens. The NSST is presently being installed in the building from which the DOT is operated and is likely to become the first solar telescope using adaptive optics to reach 0.1 arcsec resolution (be it over a small field). The NSST and the DOT are highly complementary and will often be used in tandem – the control rooms are adjacent.

[5] GREGOR: upgrade of the present German Gregory Coudé Telescope on Tenerife to 1.5 m aperture with a new feed telescope that follows the DOT example of being domeless — it will be weather-protected by a copy of the DOT clamshell canopy. This telescope will be particularly suited to high-resolution full-Stokes spectropolarimetry including the important infrared (where Zeeman splitting wins from Doppler broadening). Status: largely funded, operation foreseen after 2005.

[6] ATST: Advanced Technology Solar Telescope, a national US project to build a next-generation solar telescope of 4 m aperture. It will be an open telescope. The initial funding proposal (NSF) is being prepared and extensive site testing (including La Palma) is starting up. Operation foreseen after 2010. The emphasis will be on Stokes vector spectropolarimetry in the visible and infrared.

[7] Multi-telescope collaborations are often set up in solar physics. Most DOT observing is part of campaigns run by the EC-TMR *"European Solar Magnetometry Network"* ESMN which is coordinated by the DOT team and includes the Swedish group and access to the three other solar telescopes presently operating on the Canary Islands. None matches the DOT 0.2 arcsec angular resolution, but they do add spectropolarimetry at 0.5–1.0 arcsec resolution and in the infrared.

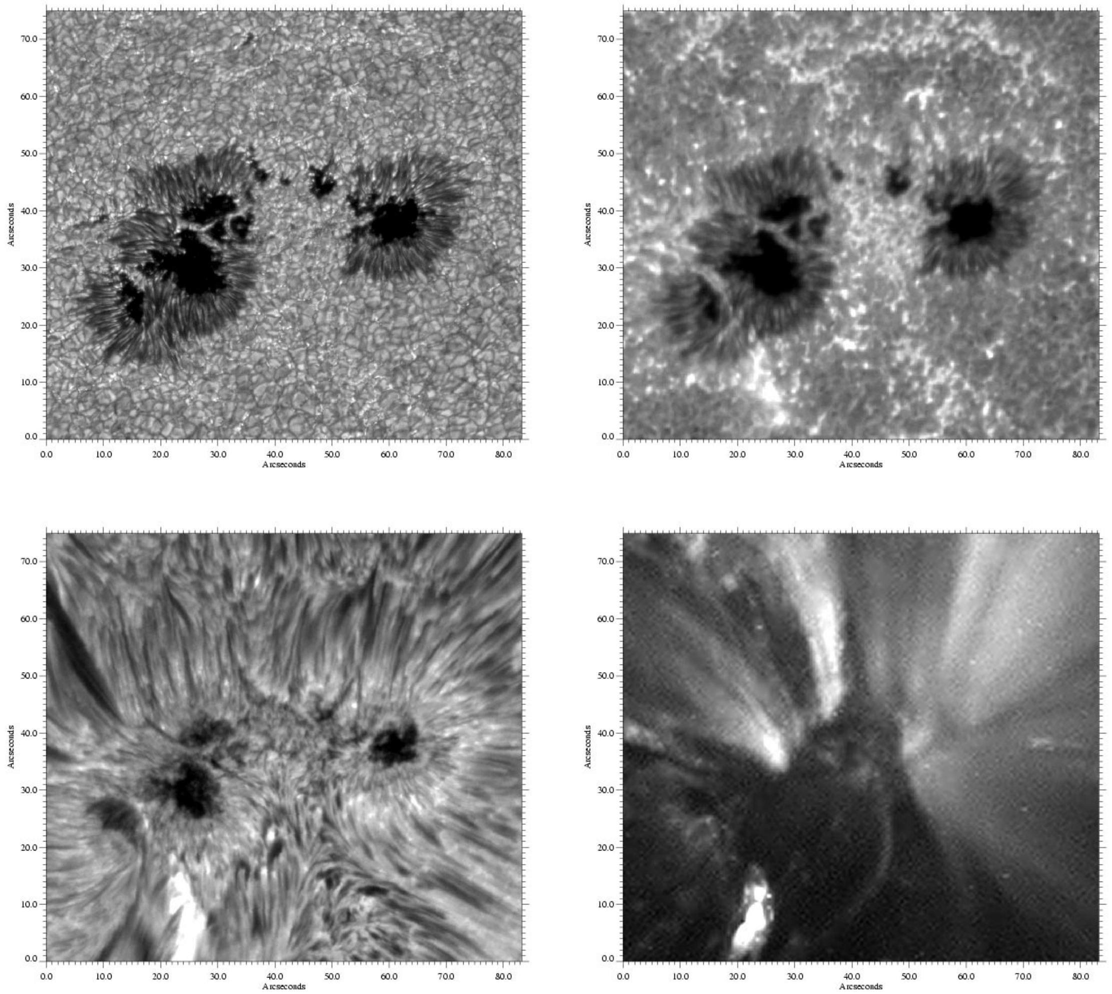

Figure 1: Tomographic imaging of the solar atmosphere (May 30, 1998). First image: solar photosphere imaged in the G band. Second: low chromosphere as sampled by the Ca II K line. Third: high chromosphere in $H\alpha$*. Fourth: one-million degree gas in the corona emitting the Fe IX/X doublet, taken with TRACE. Outside sunspots, the G band shows tiny intergranular magnetic elements which are the basic building block of solar magnetic activity. They become visible only when the resolution is better than 0.5 arcsec. The Ca II K shows the magnetic "network" made up by concentrations of the magnetic elements as bright due to magnetically induced heating. The* $H\alpha$ *line maps expanding fibrils in the transition to the corona, where the magnetic field lines constitute coronal loops sampled (at coarser resolution) by TRACE. The first three images were taken with the SVST at a brief (and rare) moment of extremely good atmospheric conditions. The multi-wavelength speckle system at the DOT enables such high-resolution multi-layer sampling continuously – in principle as long as the seeing remains reasonable (often the whole day), in practice a few hours due to data storage limitations.*

down to the slender fluxtubes that appear as tiny network bright points at high resolution. These magnetic elements are organized in intricate, continuously evolving patterns that constitute solar activity, control the structure and dynamics of the solar corona and the solar wind, and affect the extended heliosphere including the near-earth environment as well as the terrestrial climate. Their role gives threefold motivation to study solar magnetism: *(i)* – the astronomical context of stellar activity (the sun as "Stone of Rosetta star"); *(ii)* – astrophysical magnetohydrodynamics, with the sun a relatively close-by "cosmic laboratory"; *(iii)* – the solar modulation of the human environment through "space weather".

Field role tomography. The field patterning and its evolution at the solar surface are dictated by the subsurface dynamo and convective flows but in turn they dictate the structure, dynamics, and heating of the outer atmosphere. This switch in field role occurs in the optically observable photosphere–chromosphere regime, so that ground-based imaging permits charting the magnetic "footpoint" topology and dynamics. The footpoint "fluxtubes" are imaged sharpest at the base of the solar atmosphere (photosphere) when observed in the Fraunhofer G-band (a cluster of molecular lines around $\lambda = 430.5$ nm). These magnetic flux ropes bundle in clusters that can be traced up to the chromosphere through imaging in the Ca II K line, and then spread out in magnetic fibrils seen in the H I Balmer-α line. In the solar corona the field is structured in extended loops that are observable with space-based ultraviolet imaging (presently SOHO and TRACE). Figure 1 shows examples. The first three diagnostics are being implemented at the DOT in the form of synchronous speckle imaging systems for each wavelength.

Science targets. High-resolution image sequences using the tomographic multi-wavelength DOT imaging are useful and desirable to virtually *every* solar physics program addressing issues in which magnetic topology plays a role. Such issues range in spatial scale from tiny network fluxtubes to sunspots, prominences, and extended active regions, in temporal scale from high-frequency oscillations to active-region evolution, in dynamical behaviour from stable (but oscillating) sunspots to flares, erupting prominences, and coronal mass ejections, in pattern topology from ephemeral field emergence and network field dispersal to the structure and evolution of active regions and the anchor constraints to filaments/prominences and flare build-up.

Time scales. In most research topics the desire is to have high-resolution sequences sampling the solar phenomena at sufficiently fast cadence over durations as long as one can get[8]. The reason for this desire is the inherently dynamical nature of solar structures and processes over a wide range of time scales. For example, even long-lived sunspots harbour magneto-acoustic shocks and travelling MHD waves with 1–3 minute periodicity and sonic or even supersonic apparent speeds.

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[8] Obviously, the best option is to put solar telescopes in space – if cost were no concern. Weather permitting, daylight duration can be extended cheaper by round-the-world observing. In this respect, close collaboration between the DOT and the BBSO observatory operated by the New Jersey Institute of Technology at Big Bear Lake in California is a viable option, and strongly endorsed by both groups since BBSO is to a large extent the present US counterpart to La Palma. A third option to evade nightly interruptions (at least daily ones in summer) is to move the DOT to Antarctica, but apart from other considerations there has been no good-seeing site identified there so far.

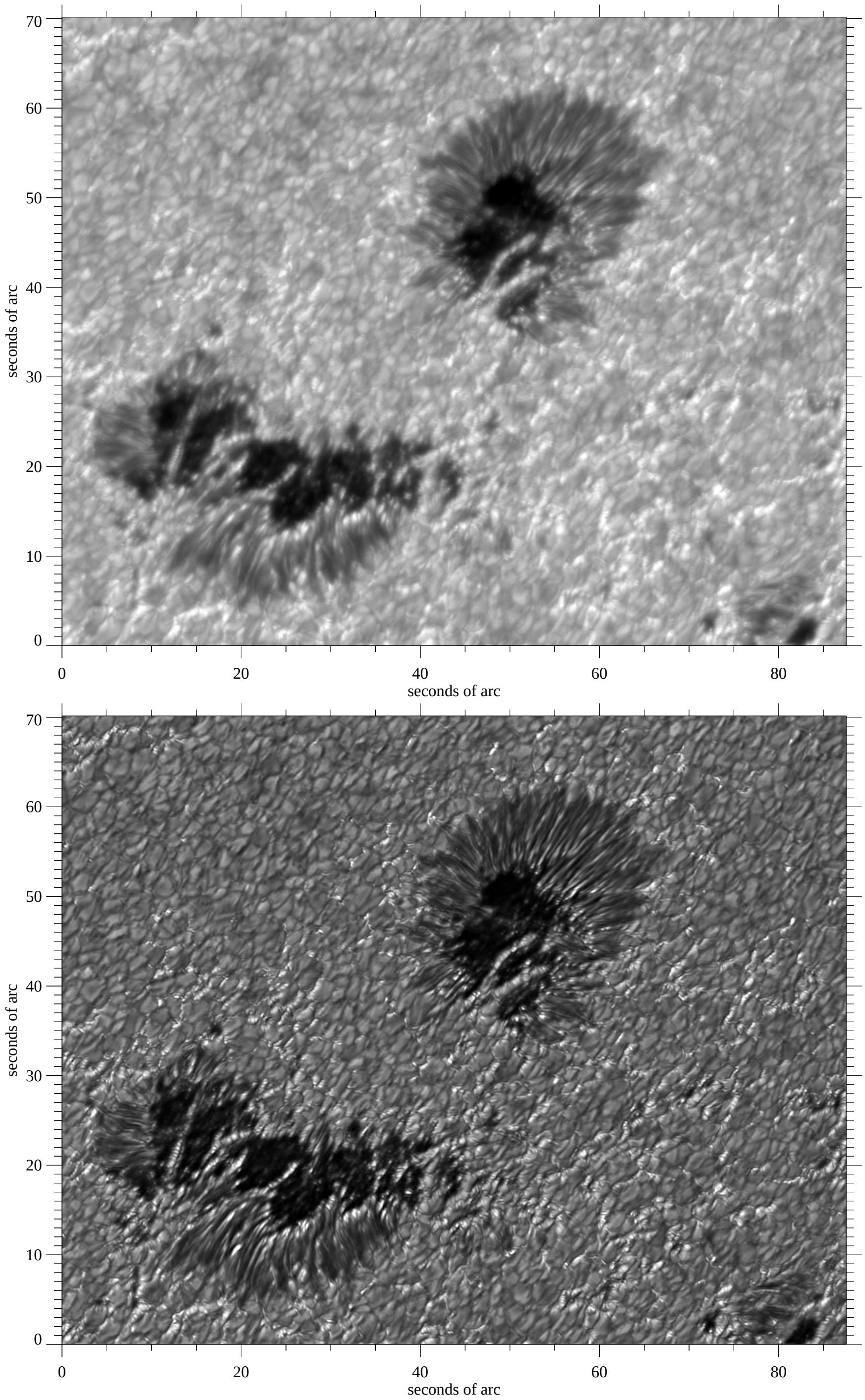

Figure 2: Example of DOT speckle restoration. The upper image is the best frame of a 100-frame speckle burst, the lower image is the speckle reconstruction from the full burst. Solar active region AR9359, February 23, 2001. Scale: 1 arcsec = 725 km on the solar surface. The DOT diffraction limit is 0.2 arcsec. Single images as this one are impressive, but the movies made from restored-image sequences (http://dot.astro.uu.nl) are even more dramatic. At their sustained high resolution they vividly demonstrate the inherently dynamical nature of solar magnetism. Even long-lived sunspots are seen to be highly dynamical structures on small scales.

3 DOT speckle imaging

Aperture. The DOT has a primary mirror of only 45 cm diameter but is not a small telescope in performance. The reason is that even at La Palma the Fried parameter r_0, which describes atmospheric quality in terms of equivalent telescope aperture, exceeds 10 cm only rarely (as in Figure 1). Super-seeing commensurate with meter-class aperture may occur in perfect La Palma weather but waiting for that is likely to take many years! Even half-meter telescopes are usually far too large. The much larger telescopes used in night-time astronomy[9] are not sharper but only collect more light[10].

Adaptive optics. This situation is changing in both solar and night-time astronomy through the advent of adaptive optics in which the atmospheric perturbation is compensated in real time by applying appropriate counter corrections at high speed to a "rubber" mirror. This technology (originally brought to astronomy courtesy of SDI star-wars programs) is revamping the use of ground-based telescopes. A major drawback, however, is that adaptive optics corrects only the center of the field of view optimally, the so-called on-axis "isoplanatic patch" which extends over only a few arcsec.

Speckle reconstruction. The DOT does not employ adaptive optics (which in solar physics elsewhere exists only as low-order test configurations at this stage), but relies on a post-processing alternative to correct the images for the remaining atmospheric degradation: speckle imaging and speckle reconstruction. The technique uses the atmospheric property that short-exposure images ($t \leq 10\,\mathrm{ms}$) freeze its wavefront distortions while still showing signal at high spatial frequencies, be it with statistically disturbed phases. By taking a large number of such short exposure images (a "speckle burst") and using an elaborate statistical model, speckle reconstruction estimates the unperturbed amplitudes and phases in Fourier space and delivers a close approximation to the unperturbed image. Figure 2 shows an actual example.

The quality reaches the theoretical resolution limit set by diffraction at the aperture diameter if the seeing is reasonable ($r_0 > 7$ cm) and sufficient independent specklegram samples of the wavefront disturbances are used (of order 100). 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 of 0.1 arcsec and horizontal velocity of 4–5 km/s in the solar atmosphere, or about 100 frames at 6 frames/s rate. (The new DOT cameras reach 11 frames/s for short exposures, the optimum rate since at higher speed successive frames are no longer independent samples of the seeing.)

The major advantage of speckle reconstruction is that it starts with tessellating the observed field in isoplanatic subfields, which are each 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. In contrast, adaptive optics does not tessellate the image but the pupil (ideally by splitting the aperture in independent subapertures smaller than r_0), making off-axis restoration ("multi-conjugate adaptive optics") difficult.

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[9] Also on La Palma, where Dutch astronomy shares in the Isaac Newton Group including the 4.2 m William Herschel Telescope. The night-time seeing on La Palma is often excellent. It presents a lower limit to day-time seeing because solar ground heating adds local turbulence while the high-altitude seeing remains the same (the limiting factor for night-time observing unless spoiled by dome seeing).

[10] Except for the Hubble Space Telescope which is located above the atmosphere.

Speckle acquisition system. The DOT has recently been equipped with a large-volume speckle data acquisition system, the largest in astronomy. It was realized by the Instrumentele Groep Fysica (IGF) at Utrecht and consists of five synchronously operated digital specklegram cameras, two-way optical fiber links transfering the speckle bursts at 1 Gb/s to the control room in the Swedish solar telescope building, five Compaq image-acquisition computers writing the data to five 72 GByte RAID disk arrays, and a Exabyte Mammoth-2 7-tape library for archiving.

With all five cameras taking 100-frame speckle bursts in 30 s cadence at their 2.7 MByte frame size, the five disk arrays fill up in a little more than two hours. Archiving the 360 GByte to tape is speed-limited by the 100 Mb/s ethernet and takes about 10 hours. Thus, the disk capacity and archiving speed limit the duration over which the DOT can collect image sequences at full clip. For some science topics one may trade the burst cadence or the number of cameras against the sequence duration, but more often the "disks full" warning will signal a harsh ending to an observing run.

The storage capacity has to be large because the subsequent speckle processing is too laborious to be achieved in real time with current off-the-shelf hardware. Since the reconstructed images themselves require only one percent of that space (100 burst frames producing one image), speckle reconstruction may be seen as a – very slow but quality enhancing – data compression algorithm.

4 DOT speckle processing

Current turnaround. The major drawback of speckle reconstruction is the large amount of subsequent processing that is needed to deliver restored images.

With the present reconstruction code, each 1296×1028 px speckle frame is split into 980 subfields measuring 64×64 px. On a single 600 MHz Pentium III processor the production of one reconstructed image from a 100-frame speckle burst takes nearly 12 CPU-hours, of which less than one hour is spent on preprocessing (frame co-alignment and tessellation) and postprocessing (subfield rejoining). The remaining time is spent on one-by-one speckle reconstruction of the 980 subfields.

Most speckle processing is presently done on the data-acquisition and control computers on La Palma[11]. Many of the DOT movies available on the DOT website were processed there remotely from Utrecht. Pre- and postprocessing are done on one 600 MHz processor, subfield restorations shared out over twelve. Reconstructing one 100-frame burst takes 105 minutes.

Five-camera benchmark run. In the near future when the installation of the multi-wavelength optics is complete, many research programs will desire all five cameras to run synchronously. Therefore, we define a "benchmark DOT observing run" as using five cameras during two hours at 30 s burst cadence, registering 120 000 speckle frames totalling 324 GByte. It should be emphasized again that the choice of two-hour duration is set by the data storage capacity, not by science desire. A 30 s burst cadence is also

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[11] These six computers (the five image-acquisition ones are dual-processor 600 MHz Compaq Proliant ML-350's) presently offer larger DOT speckle processing capability than our university environment at Utrecht. One limiting factor is the use of the licensed IDL language in the code.

rather slow for some science applications.

After speckle processing a benchmark run measures only 1200 × 2.7 = 3.3 GByte – one DAT or DVD.

Current throughput. On a single 600 MHz Pentium III processing one benchmark run would take 14 200 CPU-hours – over a year and a half. Using the present code on the six La Palma PC's takes three months of continuous processing per benchmark run.

Only very few such runs per year can therefore be managed with the current processing capability. In these circumstances, the strategy is to observe somewhat more frequently, archive each run on tape (taking 10 hours/run and 45 Euro/tape), and later select the very best run for processing and analysis[12]. Excellent DOT science can be produced in this fashion even from only one or two processed runs per year, enough to sustain solar physics PhD production at Utrecht – but opening up the DOT to the international solar physics community requires much faster throughput, and faster throughput will also greatly enhance the flexibility of DOT research at Utrecht itself. The remainder of this document discusses the necessary steps.

Parallelization test. Since the speckle-frame subfields are processed independently, parallelization is an obvious tactic to accelerate the processing. An effort to achieve this has started the past months by porting the speckle code from IDL to C and parallelizing it using the industry-standard MPI toolkit.

This effort has recently culminated in a demonstration at the Utrecht University "Clustrum" manifestation (July 9, 2001) in which the Utrecht University Linux user group ran various parallelization demonstrations on a temporary cluster assembly of 250 PC's borrowed from various university departments. The newly parallelized DOT speckle code was one of the demonstrations, was ready just in time, and ran on twelve 400 MHz PC's. Specklegrams from the initial 768×572 px DOT camera were used, with each PC reconstructing 1/12th of the 266 isoplanatic patches. The speckle reconstruction itself parallelized nearly perfectly, the pre- and postprocessing less well due too limited bandwidth, but still with a factor of 3 speedup. Each part took about 15 minutes.

The test has proven that the speckle reconstruction lends itself very well to parallelization. Further acceleration can be gained by optimizing the pre- and postprocessing and of course by using faster processors and higher network bandwidth.

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[12] This is precisely the way in which the former Swedish Vacuum Solar Telescope (SVST) was used during the last decade, in particular by the solar physics group at Lockheed-Martin in Palo Alto (who also built and run the TRACE satellite and MDI onboard SOHO). Each year they took over the SVST for months at a time, first flew in their optics and computer experts for instrumentation setup, then posted alternating teams of observers at La Palma. At the end of an observing season they brought back hundreds of DAT tapes, but eventually ended up processing, analyzing and publishing only a few. Those papers made the SVST famous by breaking the "subarcsecond barrier", but mostly in snapshots and one famous 20-minute reconstructed image sequence. The latter took many weeks of processing. Utrecht has been the only other location where SVST data from the Lockheed-Martin group were processed and analyzed using Lockheed-Martin software, but that was achieved by having PhD students spend half their time in Palo Alto. All other Lockheed-Martin DAT's from the SVST remain unanalyzed. At present, the DOT takes over the role of being the sharpest solar imager from the SVST, with the clear goal and niche to extend high-resolution observing over much longer durations. The same format of reducing just one sequence out of many taken is a viable way of producing in-house science at Utrecht, but also implies an enormous loss of potential science by the worldwide community. Mobilizing the latter requires delivery of ready-to-use data products, however.

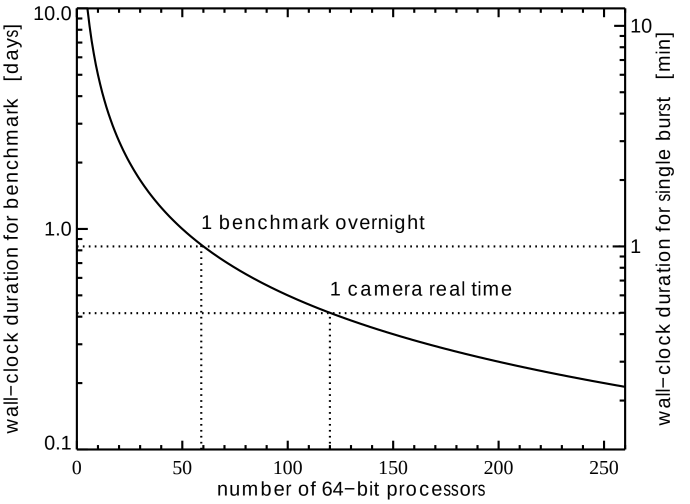

Figure 3: Estimate of the wall-clock duration required to process a DOT benchmark run (five cameras, two hour duration, 30 s burst cadence) as function of the number of 64-bit processors used. The estimate assumes that the use of Intel McKinley's and further code optimalization will gain a factor 12 speedup over 600 MHz Pentium III's. Overnight (20-hour duration) benchmark processing is achievable with a 64-node cluster. The righthand axis shows the corresponding processing time per single burst in minutes. Keeping up with five cameras in real time would require ten times as many processors (neglecting network bandwidth limitations).

Further tests. The successful porting from IDL to C enables wider application of the code. At present, a 16-node cluster consisting of discarded 180 MHz Pentium Pro computers is being assembled for further tests and code optimalization. Other tests may involve an 8-processor SGI Origin at the Utrecht Physics & Astronomy department, a new 64-node cluster linked through Myrinet, and SARA's TERAS facility.

Overnight turnaround on site. Overnight turnaround of the speckle processing at the telescope is the goal to reach in throughput acceleration, where "overnight" means processing duration of say 20 hours for a two-hour run. It will clean the disks in time for a new run the next day without need for 10-hour archiving on tape. When larger disks become affordable, the run duration and/or cadence frequency may then increase accordingly[13].

Figure 3 summarizes the dependence of speckle pipeline speed on the number of processors used in parallel operation, based on the above experience. The wall-clock duration along the y-axis gives the time it will take a cluster of the size specified along the x-axis to process one benchmark run. The processors are assumed to be upcoming state-of-the-art 64-bit architecture ones such as Intel McKinley's. The conclusion is that it takes a 64-node cluster of these to achieve overnight benchmark turnaround. A 64-node cluster of currently available HP-Compaq Alpha's would need a few days per benchmark.

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[13] Real-time speckle processing sounds even better since it would remove any storage limitation, but that requires ten times as many processors and very high connection bandwidth.

5 The DOT as common-user telescope

Open policy. Most solar telescopes are common-user facilities open to the wide community. The general solar physics policy is to welcome observing proposals from anywhere and to schedule them on the basis of merit alone, without limiting telescope access to proprietary institutions or nations[14]. The general practice is also to do this without costing. The successful proposer is often asked to run or assist in running the program, and sometimes to provide the tapes needed to take his/her data home.

Such open policy illustrates an important characteristic of solar physics: it is a field of large-scale international cooperation rather than secretive competition. The background is simply that on the one hand there aren't that many solar physicists while on the other hand our sun poses exceedingly complex questions requiring holistic rather than isolationist approaches. The increasingly frequent multi-telescope campaigns (including space missions) concentrating on one particular solar issue illustrate this practice of wide collaboration.

Present DOT policy. At present, the DOT team adheres to the open data policy in the sense that all DOT images and movies are available to researchers anywhere, but it does not support common-user DOT availability. The reasons are twofold: the DOT team is too small to support frequent observing, and processing more than a few runs per year is presently impossible as discussed above.

Opening the DOT. It will be a boon to solar physics in general if the DOT is turned into a common-user facility: one that observes much more frequently than a few runs per year, that co-observes regularly in international multi-telescope campaigns, and that welcomes external observers with sound proposals (through a peer-review allocation procedure) – in brief, to let the DOT fill its science niche to the full niche capacity rather than be limited operationally. Opening up the DOT will also be a boon to Dutch solar physics by strongly enhancing the DOT visibility, merging the DOT in extensive international research programs – and boosting the number of DOT-based publications.

Three steps are necessary to turn the DOT into an "open" telescope in the sense of a common-user facility:

- achieve overnight on-site processing as described above;
- make the DOT safe and easy to operate;
- increase the on-site DOT manpower for frequent observing.

Data delivery. The first task, overnight processing, must obviously be realized first because frequent observing makes sense only if the finished data product (sharp image sequences) is delivered fast and without impeding the next observing run.

Foolproof observing. The second task is one that has been recommended as high priority by the DOT Evaluation Committee *("The DOT should be brought to a state where it can be operated in a safe and reliable fashion by a trained person.")*. The background is that so far, both DOT engineers (R.H. Hammerschlag and F.C.M. Bettonvil) must be

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[14] For example, Utrecht solar physicsts have been frequent users of the major US National Solar Observatory telescopes on Kitt Peak and Sacramento Peak and of the SVST on La Palma, and have been welcome at many other facilities. The same open policy applies to space missions: all TRACE data and most SOHO data are directly web-available while access to the remaining data from space is easily arranged through contacting the PI. All data become public after one year anyhow.

present during observing because many operational procedures (including opening and closing the canopy) harbour large risk to the telescope. DOT observing and DOT development therefore clash by competing for engineer time at present. The task is to make DOT usage foolproof for other observers, from Utrecht and elsewhere. Fail-safing the DOT operation has been embarked on in the meantime. It will greatly facilitate manning the DOT for more frequent observing

Traineeship program. The third task can be partially accomplished by asking external DOT users to come to the DOT at assist in observing and processing. In addition, an INTAS grant to the DOT team will enable experienced solar instrumentalists from Kiev and Irkutsk to come help out at the DOT. A very attractive option to increase the on-site manpower is to start a DOT traineeship program bringing students to La Palma. They may come from astronomy, physics, computational physics or computer sciences, and they will gain hands-on experience with a state-of-the-art telescope and with state-of-the-art computation, in the context of international campaigns and at the major astronomical observatory in Europe. A desirable scheme would be to schedule regular student assistence during the four summer months (when the weather is frequently good and when student curriculae permit absences) in two-week slots per student, with one week overlaps and midstay junior/senior duty changes. Such a program will bring up to 18 students yearly to the DOT and enhance their education.

Investments. The parallelization test and an initial inventory of the hardware offered by the major vendors indicate that the installation of overnight processing hardware requires about 400 kEuro. The DOT safeguarding may be accelerated through investing two engineer-years of effort. The traineeship program will take 18 kEuro/year.

6 The DOT as remote telescope

Fast phenomena. Many international multi-telescope campaigns address phenomena related to solar activity and therefore require selection of the common field of view on short to very short notice (the latter for example when observing flares or filament eruptions). In addition, spectrometers use narrow (1 arcsec or less) slits which are stepped over narrow strips or even held stationary. Co-pointing diverse instruments at different telescopes is therefore greatly assisted by facilities for (nearly) instantaneous remote targeting[15].

Remote DOT pointing. Since the DOT is a wide-field imager, the co-pointing constraints are much easier than for a slit spectrometer or a small-field adaptive-optics imager. The remote-targeting facilities can therefore be limited to supplying snapshot images at regular but slow cadence (say one per minute) and an interface for slow-response telescope pointing. The images only have to offer medium (non-restored) quality and can therefore

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[15] Remote targeting should not be interpreted as remote telescope operation without local observer. Remote operation may be feasible for the DOT (which will be remotely operated from the Swedish building anyhow when the safeguarding is complete) but not on a short timescale. First, procedures such as telescope focusing require very high bandwidth. Second, it is too risky. The experience at the night-time telescope of the Apache Point Observatory (New Mexico) which is explicitly designed for internet control (exploiting the fact that it specializes on deep exposures which take hours to fill a few MByte) is negative with regards to risk. For example, remote observers do not hasten to kill their exposure and close the dome when it starts raining.

be served by a frame-selection code running parallel to the speckle data acquisition, with jpeg compression for fast internet access. The pointing interface can be a low-bandwidth emulation of the actual telescope control interface in the DOT control room (already remote), addressing the latter instead of the telescope itself.

DOT pointing from Utrecht. DOT participation in multi-telescope campaigns is the principal motivation for such remote targeting via the web, but it will obviously also enhance telescope exploitation by the DOT team itself, for example through letting staff at Utrecht "look over the shoulder" of observers on La Palma. Teaching duties at Utrecht may so be fulfilled while co-running observing programs at La Palma.

Investment. This task primarily asks software engineering in the form of two person-year effort at engineer level.

7 The DOT as virtual telescope

Virtual Solar Observatory. The internet presently revamps astronomy including solar physics as least as much as it changes general society. It seems inevitable that the "Virtual Solar Observatory" (VSO) consisting of streamlined search engines into databases and real-time data streams will greatly change solar physics in the near future, and dominate solar physics on a longer time scale.

The documents and the mock-up demo site of the US National Solar Observatory (http://www.nso.noao.edu/vso) signify the way it will go. A fair prediction seems that solar facilities which do not join this development in time run the risk of dropping out of the picture altogether.

In Europe, the push towards virtual observatories has started for night-time astronomy in the EC-supported ASTROVIRTEL project on behalf of ESA and ESO and aims at integration of the databases from ESA's space-based and ESO's Chile-based facilities. European solar physics has web-accessible database projects in France (Toulouse) and Italy (Naples), but is yet far from an integrated European VSO. Nevertheless, it will come, and likely will be integrated with the American one into a worldwide VSO.

Dot entry in VSO. Assuming that the DOT evolves into a frequently used observing facility as described above and will build up a sizable database of high-resolution image sequences, two conditions must be met to integrate the DOT into the future VSO:
- sufficient web-accessible server capacity;
- sufficient web-access bandwidth.

Investments. The first requirement is minor. One DOT benchmark run, or even a full-day run when the speckle disks get large enough, fits on a single DVD after the hundredfold compression through speckle reconstruction. A DVD jukebox will serve the initial need.

The second requirement implies much higher bandwidth to the Canary Islands than the meager 2 Mb/s presently available. This is not a task to be realized by a small team with modest means but, in contrast, seems one for the EC whose 6th Framework Programme will pledge to enrich the "European research area" through (http://europa.eu.int/comm/research/area.html):
- optimising European level infrastructures,

– establishing networking centres of excellence,
– establishing virtual centres and maximize electronic networks,

which together with EC's view of the Canary Islands as a "less-favoured region" (not true in astronomical seeing) implies that Dynacore-like efforts will at some time establish higher bandwidth to all telescopes at the Canary Island observatories, not just the DOT. However, the DOT team can play a role through its ESMN leadership in integrating and representing the European solar physics community in such proposals.

Conclusion

In summary, we conclude that the following steps should be taken sequentially the coming years to enhance the role of the Dutch Open Telescope in worldwide solar physics:

(a) – *achieve hundred-fold data compression at the telescope by accelerating the on-site speckle processing to overnight turnaround.*

This step can be taken now by installing a 64-node cluster of state-of-the-art 64-bit processors in the Swedish telescope building on La Palma together with optimization of the parallel speckle code. The effect on DOT imaging output will be dramatic.

(b) – *turn the DOT into a common user facility.*

This step will strongly enhance the international DOT visibility and science output, and will also turn the DOT into a valuable asset to education through a student traineeship program in the summer months.

(c) – *implement user interfaces for remote targeting via the web.*

A smaller step, mostly requiring software engineering.

(d) – *install the server capacity needed to make the DOT an integral part of the Virtual Solar Observatory.*

To be installed when the DOT starts collecting sizable image sequences through frequent observing.

(e) – *increase the bandwidth to La Palma sufficiently to enable fast image retrieval from abroad.*

A step to be taken through EC funding in European context.

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