SOLAR PHYSICS AT STATE-OF-THE-ART RESOLUTION

Preliminary proposal for NOVA phase 2

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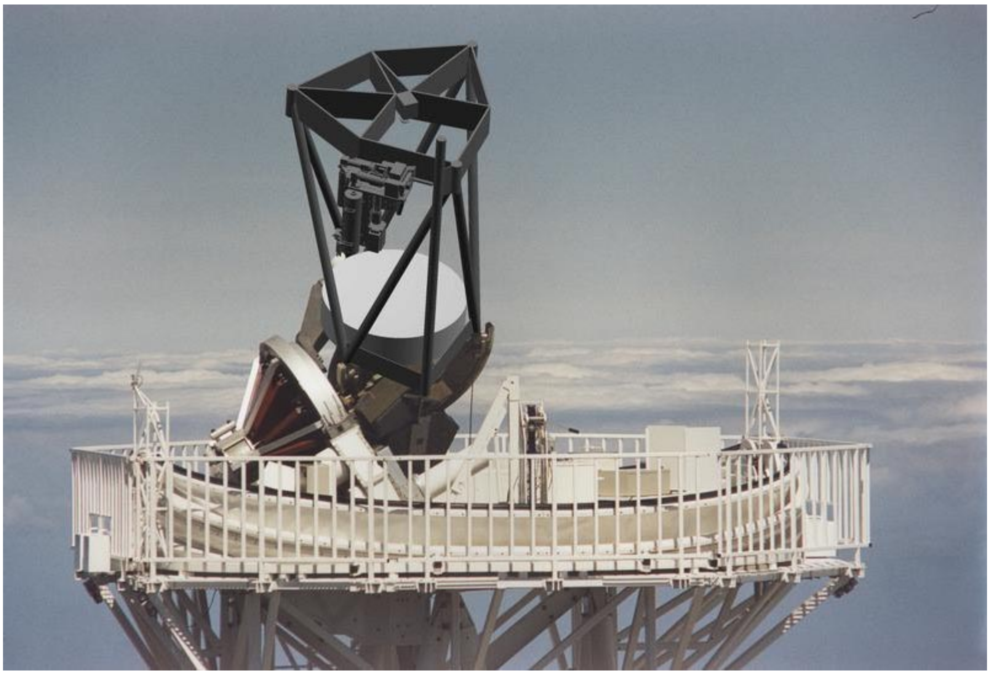


1.4-m aperture design drawing superimposed on DOT photograph

Summary

The *Dutch Open Telescope* (DOT) 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 image restoration through speckle interferometry.

In the past three years the DOT became the first solar telescope to regularly obtain $0.2''$ resolution in extended image sequences, *i.e.,* reaching the diffraction limit of its 45-cm primary mirror. Its example is now followed in major solar-telescope projects elsewhere. Our aim for 2003–2005 is to turn the DOT into a tomographic mapper of the solar atmosphere with frequent partnership in international multi-telescope campaigns through student-serviced time allocation.

This proposal for NOVA phase 2 requests support to triple the DOT resolution to $0.07''$ by increasing the aperture to 140 cm in 2006. It will maintain the DOT's role as tomographic context imager at the resolution reached in simultaneous adaptive-optics spectropolarimetry elsewhere. In addition, subsequent renewal of the speckle pipeline is requested which will give the DOT an unparalleled field of view.

The upgrade will give this 100% Dutch telescope a unique niche in high-resolution solar physics well beyond the Solar-B imaging capabilities and highly complementary to the SDO mission.

Team and PI. The DOT team consists currently of Dr. R.J. Rutten (UU; project scientist), Dr. Ir. R.H. Hammerschlag (UU; project engineer), Dr. P. Sütterlin (NWO), Ir. F.C.M. Bettonvil (NWO via ASTRON), and students. The present proposal comes from this team with R.J. Rutten as PI. The PI-ship is likely to shift to the new UU chair in solar physics.

Science context. Solar physics is primarily 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, organised into intricate activity patterns in the photosphere, dominate the structure of the chromosphere and corona at any scale, regulate the solar wind, and affect the extended heliosphere including near-earth space weather and the terrestrial climate. 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 and SDO will set the stage.

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

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. Most of the DOT movies collected so far 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) follow this autumn; the final two (tunable Lyot filters for Hα and Ba II 455.4 nm) will be installed next year. The combined multi-wavelength speckle imaging will make the DOT the premier tomographic imager of the magnetic fine structure, topology, and dynamics of the photosphere, low chromosphere and high chromosphere all at the same time.

Our next short-term goal is to vigorously exploit this high-resolution tomography capability by frequent sharing in international observing campaigns and so increase the DOT science production and visibility by a considerable factor. Our present computer power limits the DOT speckle processing to only a few multi-wavelength image sequences per year, which do suffice for the research needs of the present UU solar physics group but severely underuse the DOT full science capability. We therefore aim to install a large-capacity speckle-processing system and to initiate a student-service program bringing many Dutch students to La Palma to assist in the observing (details in a White Paper on the DOT website). The latter two steps are yet unfunded, but we assume them here as taken by the end of 2004 so that the DOT will then fully fill its niche of tomographic mapper at $0.2''$ resolution within collaborative multi-diagnostic multi-telescope programs.

International context. Multiple solar telescope projects now aim at the $0.1''$ barrier relying on adaptive optics. The first to reach it is the New Swedish Solar Telescope (NSST), a 96-cm aperture vacuum refractor which recently replaced the 48-cm SVST. Its initial 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 NSST now becomes the sharpest solar telescope and will remain that for some years. The DOT, operated from the NSST 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. Operation is likely by 2006.

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 a candidate). The principal aperture driver is photon flux for precision polarimetry at about $0.1''$ resolution. First light perhaps by 2010.

These new adaptive-optics telescopes will emphasize Stokes magnetometry with Fabry-Perot filtergraphs and grating spectrometers[1]. The DOT's wide-field multi-wavelength speckle imaging remains complementary as tomographic context mapper. However, its 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 similarly attain wide-field multi-wavelength $0.2''$ resolution — without interruptions from bad seeing, bad weather, nights, or operational constraints.

Solar-B will not fully kill the DOT's present niche since one single telescope will not meet all science needs ("one Keck isn't enough"; *e.g.,* mapping both anchor regions of a coronal loop requires two such high-resolution imagers). However, the DOT aperture tripling proposed here will fully regain the DOT's role of tomographic imager in the Solar-B era and 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 at $0.2''$.

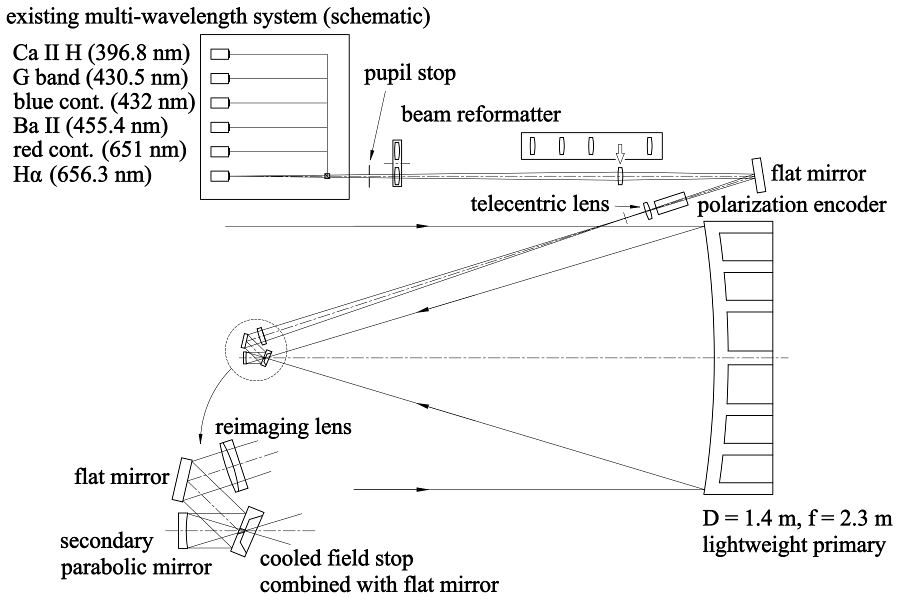
NASA's large *Solar Dynamics Observatory* (SDO), effectively the successor to both SOHO and TRACE to be launched in 2007, will use many 4K×4K detectors for continuous simultaneous high-cadence full-disk imaging in Stokes V, Doppler and many EUV wavelengths with $1''$ resolution, furnishing whole disk and coronal complementarity to all groundbased high-resolution telescopes all the time. Combination of imaging and spectropolarimetry at the latter with SDO's comprehensiviness is likely to revamp solar physics.

Dutch context. This proposal fits renewed Dutch interest in solar astrophysics. The Utrecht faculty has recently decided to strengthen UU solar physics by instating a solar physics chair; a search committee is being formed. It is highly unlikely that the incumbent will not support the present proposal and be willing to become PI. Furthermore, J.M.E. Kuijpers' move to Nijmegen implies new solar physics interest there. The plasma physics theory group at Rijnhuizen (FOM) remains devoted to solar physics (J. Goedbloed, R. Keppens).

Realisation of this proposal makes The Netherlands compete at the high-resolution solar physics frontier with a unique Dutch facility, at a fraction of the cost of any other solar telescope project. Much student involvement is foreseen.

Technical outline. 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

[1]The same holds for the German-led *Sunrise* proposal aiming at balloon-borne spectropolarimetry with 1 m aperture.



Optics design for DOT aperture tripling using the present multi-wavelength system

systems[2] will remain intact and be remounted on a new telescope-top support structure besides the incoming beam. 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).

A fairly detailed design has been made to verify the opto-mechanical feasibility (see diagram). 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 three flat folding mirrors to the multi-channel system. A telecentric region may harbour polarization encoders for Stokes and Hanle Ba II 455.4 nm magnetometry. The beam formatter permits tradeoff choice between resolution and field.

Technical considerations. The effectiviness of speckle reconstruction diminishes with aperture size. Actual solar speckle reconstruction with the German VTT (70 cm) on Tenerife and night-time speckle reconstructions with telescopes up to 6 m diameter give confidence that solar speckle reconstruction remains viable at 140 cm, but it will require appreciably better seeing to obtain complete restoration (to the diffraction limit) than at 45 cm. At other times the appropriate $0.025''$/px image scale represents wasteful oversampling which unnecessarily limits the actual field of view set by the chip size. Hence the addition of a beam reformatter to trade field against resolution, for example giving preference to a larger field during less than superb seeing to catch a flare or prominence eruption.

The introduction of a parabolic secondary mirror will fully cancel optical aberrations from the parabolic primary which presently limit the useful DOT field of view to three arcmin. Since much larger CCD chips with the 10 frames/s readout speed needed for speckle burst registration should become affordable with time, we intend later in this decade to revamp the DOT cameras and

[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 600 Mhz PC with 72 GB disks in the Swedish building. This storage capacity limits the observing duration to 2.2 hours at 30 s speckle burst cadence.

speckle pipeline with state-of-the-art hardware, and so increase the field of view considerably at any resolution. For example, during non-superb seeing 4K×4K chips would register $300'' \times 300''$ at $0.2''$ resolution, over four times the maximum Solar-B field of view, and enable studies of the topology and dynamics of whole active regions including complete coronal loop anchoring. When the seeing turns excellent — as flagged by our reliable scintillometer — shift to $0.07''$ resolution then reduces the field to $100'' \times 100''$, still large enough to contain a complete mature sunspot with its moat.

Costs. The total cost of the aperture tripling amounts to 550–750 k€, with the variation largely determined by the mirror material. The ideal material is SiC. It presently spawns much new telescope technology because it combines large strength with extremely low weight, enabling self-support mounting, and also has excellent heat conduction. However, the price for a 140-cm SiC blank is at least 250 k€ at present and the fabrication unproven. Prices should drop somewhat and it is not unlikely that leftover spare blanks from other projects (*e.g.,* GREGOR) may be had at lower cost. The alternatives are Zerodur or possibly even borosilicate blanks, requiring a much more elaborate support structure but with blank prices dropping as low as 50 k€. Figuring and polishing will add about 200 k€ in each case.

The remaining aperture-tripling costs are estimated to be 50 k€ for the heat-rejecting field stop plus backside mirror in the primary focus, 100 k€ for the relay and reformatting optics, 100 k€ for the new telescope top, and 50 k€ for the development work and extensive tests needed to optimize the optics and mechanical construction. These estimates include outsourcing.

The replacement of the speckle system by state-of-the-art cameras, data storage and speckle processing systems which we envisage as the major step after the DOT aperture tripling, to be taken toward the end of the decade when much of the present system will be obsolete, is hard to cost-estimate at present. A first guess assumes 120 k€ for 6 cameras and 300 k€ for an appropriately wide and fast speckle pipeline.

DOT-team manpower is not included in these cost estimates.

Contributions by others. The present DOT funding (including the contracts of Bettonvil and Sütterlin, both indispensable as confirmed by the DOT Evaluation Committee) ends before the start of NOVA phase 2. This proposal is obviously submitted in the expectation that the DOT continues to exist after 2005. It is also obvious that the DOT future is contingent on a UU policy decision involving the new chair in solar physics.

Outline of project management. The basic designs for the aperture increase will be done by the DOT engineers. Completion of the multi-channel imaging system will free them for this effort by 2004. Bettonvil is envisaged as project manager. Progress reporting will adhere to NOVA rules. Much outsourcing of detailed design verification, optics component tests, quality control, and small-component fabrication to ASTRON is foreseen. The new telescope top will be a relatively simple mechanical structure (most complexity lies in the existing multi-channel system), which can be constructed at the Utrecht (IGF) and Delft (DTO) workshops with specialist tasks performed by industry. The assembly, alignment and testing of the new top will be done at Utrecht, Delft or Dwingeloo. The total time to completion is estimated to be two years. The actual change-over from old to new DOT top including the remounting of the multi-channel system will be a matter of weeks and not seriously interrupt DOT science utilisation.

Subsequent renewal of the speckle system will mostly entail fairly straightforward hardware procurement unless LOFAR-like special-processor solutions are sought. Expert advice will come from UU (Ir. A. van der Steen's group), ASTRON, and elsewhere.