Instrumentation for the Dutch Open Telescope

Request for funding by NOVA

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SUMMARY

The Dutch Open Telescope (DOT) is a new and novel optical solar telescope on La Palma. Its completion and installation up to first light have been funded by STW out of technological interest. This document summarizes the DOT science capability and specifies the basic post-focus instrumentation that is needed for initial DOT science utilization. It consists of three-channel narrow-band imaging in the Fraunhofer G band, Ca II K and Hα, and will enable simultaneous high-resolution "proxy"-magnetometry of the solar photosphere, lower chromosphere and upper chromosphere in concert with the SOHO and TRACE space missions. NOVA funding is requested for the instrumentation part.

DOT images and photographs: `http://www.fys.ruu.nl/~rutten/dot/Home.html`

1 Optical solar physics

1.1 Solar physics overview

Our sun is an ordinary dwarf star. However, for earth-bound astronomers the sun is a special star by being the only one close-up — the next ones are smaller on our sky than a solar granule. Close up, the sun shows a wealth of fine structure due to its convection and, in particular, its magnetic field. The underlying processes are common across astrophysics but they can only be studied in detail on the sun, making solar physics "the mother of astrophysics". For example, at Utrecht the solar physics tradition has inspired much research in cool-star activity, stellar flares and other energy release processes, and the magnetohydrodynamics of accretion disks.

To earth-bound physicists the solar atmosphere provides structures and dynamical processes at regimes of temperature, density, magnetic field strength and spatial dimensions that are impossible to simulate in a terrestrial laboratory. Plasma physicists in particular turn increasingly to the sun to study magnetism-controlled phenomena that provide complementary insight to studies employing plasma machines such as Tokamaks. This trend is exemplified by Goedbloed's theory group at the main Dutch plasma physics research institution (FOM Instituut voor Plasmafysica Rijnhuizen, Nieuwegein) which concentrates on solar plasma physics.

For the rest of our planet's inhabitants, the sun is primarily the source of life-sustaining light. Variations in the solar output affect mankind directly; fortunately, these are very small. However, the solar wind and solar activity do affect our technological environment (satellites, communication links) through their impact on the terrestrial magnetosphere, and there are indications that the variability of solar activity contributes significantly to global climate changes. These influences make solar physics a branch of astrophysics with direct human interest.

Magnetism lies at the root of most issues in solar and heliospheric physics. The sun's magnetic field is generated by enigmatic dynamo processes in the solar interior, is organised into the highly complex patterns of solar activity that are observed on the solar surface (photosphere), dominates the structure of the outer solar atmosphere (chromosphere, transition region, corona), regulates the solar wind, and affects the whole extended heliosphere. The complexities of solar magnetism are the prime reason why solar physics has a rich science content, why optical observations provide its most important diagnostics, and why it is necessary to observe the solar surface with high angular resolution.

At optical wavelengths the solar radiation represents the bulk of the energy flux that leaves the sun, making the thin photosphere where the light escapes the apparent solar "surface". It represents a very special regime in the solar stratification because it is also the layer where thermal physics gives way to nonthermal physics, and where the magnetic field gains dominance over the gas pressure. Below it, the sun is structured hydrodynamically, with turbulent convection, large-scale circulation and pressure eigenmode vibrations as the main agents and all radiation locally confined. Above it, the magnetic field dictates the structure and dynamics of the outer atmosphere and in fact the whole heliosphere.

All solar interests, whether part of astrophysics, physics, or ecosphere sciences, require high-resolution observation of the solar surface, in particular of the varying magnetic elements. The Dutch Open Telescope (DOT) embodies a new and promising approach to high-resolution solar surface observing. The DOT efforts are driven by astrophysical interest, but may eventually contribute also to plasma physics and solar-terrestrial science.

1.2 Solar surface magnetism

The solar magnetic field is highly intricate and has very discrete character, quite different from the smooth near-dipole field of our planet. The magnetic structures and patterns at the solar surface display on the one hand the enigmatic workings of the solar dynamo, hidden below the surface, and on the other hand display the boundary constraints ("footpoint motions") that control the structure and dynamics of the upper atmosphere — including the processes that cause chromospheric and coronal heating.

At the surface, the solar magnetic field consists of a remarkable hierarchy of discrete strong-field structures of which the *flux tube*, a key concept of MHD astrophysics, is the basic entity. The flux tubes are arranged into a coarse network pattern regulated by surface flows and occur in larger density in solar plage (faculae). The flows are imposed by the turbulent convection of which the granulation pancake pattern is the most evident characteristic. The solar granulation is now basically understood but the dynamical interaction between convection and flux tubes is not. Nor is the topology of the flux tubes themselves. They supposedly expand upwards to merge into magnetic "canopies" just above the photosphere, but this prediction has not been verified. Charting flux tube topology has high priority in understanding the basics of solar magnetism. The same holds for the larger elements in the magnetic hierarchy, pores, umbrae, large spots with penumbrae, and fully-developed active regions. Current results on spot topology indicate the presence of much shear between horizontally and upwards directed penumbral field bundles, while the nature and cause of umbral fine structure has not been identified.

A general paradigm of cool-star activity studies postulates that stellar coronas and chromospheres are heated magnetically, but we don't know how. Since the fields are anchored in the dense gas at the surface, the dynamics of flux tubes, pores and spots lie at the root of all outer-atmosphere heating. Thus, a fundamental goal in solar magnetism research is to measure the motions that convection imposes on the magnetic elements and to find how these control the dynamics of the outer atmosphere. It is already clear that the internetwork, network and active region chromospheres differ markedly in dynamic characteristics and response to the surface pistons and their reshuffling. The long-held concept of a quiet-sun chromospheric temperature rise has recently been replaced by a very dynamical picture of acoustic shock interference in the non-magnetic internetwork regime, but the magnetism-dominated dynamical structuring of the network is yet unclear.

On a larger scale the emergence and disappearance patterns of magnetic flux on the solar surface betray the workings of the solar dynamo. Active regions are assembled from emerging flux bundles that drain through convective collapse. The nearly E–W orientation of the great majority of bipolar active regions together with Hale's polarity laws indicate that Ω-shaped loops emerge from toroidal flux ropes which probably originate in an overshoot shell underneath the solar convection zone. Currently, helioseismology boosts global dynamo insight by mapping subsurface flows and temperature gradients. Solar surface studies should establish the required upper boundary constraints to the dynamo by identifying the processes and topology of flux emergence and disappearance. This should be done at the fundamental level of individual flux tubes.

Reference: "Solar Surface Magnetism", Edited by R.J. Rutten and C.J. Schrijver, NATO ASI Series C433, Kluwer, Dordrecht, 1994

1.3 Solar magnetometry

Much of the research summarized above relies heavily on solar magnetometry, *i.e.,* charting the structure, topology and dynamics of the magnetic elements on the solar surface and the patterns which they constitute. Particularly fruitful is the combination of ground-based magnetometry with space spectrometry and imaging of the transition region. Such co-observing permits to correlate and trace surface motions and corresponding upper-atmosphere dynamics in magnetic structures in tomographical fashion. The ground-based optical observing should provide the high angular resolution that is needed to identify, trace and track the individual field elements, in particular strong-field flux tubes, while the lower-resolution but uninterrupted viewing from space provides the long data sequences needed for coarser pattern evolution studies. Likewise, ground-based observing should chart the magnetic structures as a function of height throughout the photosphere and the chromosphere, while the ultraviolet and soft X-ray imagers in space sample the transition region and corona higher up.

At present, such multi-domain studies are possible through combining high-resolution ground-based magnetometry with the low-resolution magnetometry provided by the Lockheed-Stanford SOI/MDI instrument on SOHO and with the upper-atmosphere diagnostics provided by SOHO's ultraviolet spectrometers (CDS and SUMER), ultraviolet imager (EIT), and especially with the 1-arcsec ultraviolet image sequences from TRACE (a NASA "small explorer" mission launched April 1, 1998). From 2004 the Japanese-US Solar-B mission, successor to Yohkoh, will be the main solar physics space platform.

At present, solar activity is on the rise. It will reach maximum medio 2000. This makes high-resolution magnetometry particularly desirable during the coming years of waxing and waning solar magnetism.

The essential requirement for solar surface magnetometry is high angular resolution, well beyond the 1.5 arcsec resolution provided by SOI/MDI. The emphasis in ground-based solar observing in general is to make the best out of the seeing and to improve it and on it by whatever means feasible. This is the field in which the DOT can be an important player.

1.3.1 Proxy magnetometry

The highest angular resolution in solar magnetometry is reached by "proxy" magnetometry consisting of narrow-band imaging in which specific spectral diagnostics betray the presence and structure of discrete magnetic elements and their fine structure. The principal proxy diagnostics are the Fraunhofer G band (CH band head) at 430.5 nm which samples the deep photosphere, the Ca II H & K resonance lines (393 and 397 nm) which sample the low chromosphere, and the H I Balmer-α (Hα) line at 656 nm which samples the upper chromosphere. Each of these provides excellent proxy magnetometry; their combination is highly tomographic. At high resolution the G band displays the tiny photospheric flux tubes as tiny bright points located in the intergranular lanes; so far this is the only way short of speckle interferometry to identify flux tubes directly. Ca II K charts the magnetic network in the lower and middle chromosphere, and also displays acoustic modulation patterns in the internetwork regions as well as occasional internetwork "flashers" that mark loose patches of relatively strong, probably just emerged, magnetic field. Hα maps the overlying canopy topology, and may be used to diagnose canopy dynamics when rapid bandpass switching permits separation of Doppler and brightness modulation.

1.3.2 Stokes vector magnetometry

The next step in solar magnetometry is to obtain quantitative measurements of the magnetic field, preferably in the form of full Stokes-vector polarimetry which delivers both the field vector magnitude and vector direction. It is particularly important because there is no way yet to measure magnetic fields in the higher layers where they fully control the local structuring and dynamics. However, except at exceptional seeing the angular resolution obtained in Stokes polarimetry is less than for proxy magnetometry because long exposures are needed to obtain sufficient signal-to-noise in the narrow spectral passbands that are required for subsequent polarimetric inversion.

1.3.3 Angular resolution

The basic structures in the solar photosphere have intrinsic length scales that are set by fundamental physics processes. They are directly related to the local pressure scale height and the photon mean free path length, measuring about 50–150 km in the photosphere. As a result, the diameters of the strong-field flux tubes that constitute the major field pattern ingredient are about 0.1–0.2 arcsec on the apparent solar disk. Only at seeing and telescope resolution better than 0.5 arcsec do the flux tubes become well visible when observed in the G band. When the seeing is closer to the 1 arcsec level they vanish rapidly because their smeared-out peak brightness cancels against the dark surrounding of the embedding intergranular lane.

Sub–0.5 arcsec resolution is in reach only at optical wavelengths and (sofar) only at the Canary Islands. However, even at La Palma "super-seeing" is rare. Collecting long-duration sequences of the quality that is needed to localize and track individual flux tubes requires seeing that may occur only a few dozen times a year. The new technique of phase-diverse speckle restoration promises a dramatic improvement by providing effective super-seeing resolution when the seeing is only fair to good. The technique has been demonstrated but not put into regular use. It is highly demanding computationally, but should be easier (faster) to realize than solar image improvement through real-time adaptive optics.

Reference: Paxman R.G., Seldin J.H, Löfdahl M.G., Scharmer G.B., Keller Chr., 1996, "Evaluation of Phase-Diversity Techniques for Solar-Image Restoration", Astrophys. J. 466, 1087

2 The Dutch Open Telescope

2.1 Overview

The Dutch Open Telescope (DOT) was envisioned long ago by C. Zwaan as a facility to map and understand solar magnetism at high angular resolution. This research topic remains its first priority. Even though the realization of the DOT has taken very long, its high-resolution capability yet promises a major role in this field.

The DOT is now installed at the Roque de los Muchachos Observatory on La Palma. Photographs, diagrams, first images and other information are available at the DOT website[1].

The novel open design of the DOT exploits the often excellent La Palma conditions through minimal obstruction to the strong trade winds that bring the best seeing. The telescope and the support tower are both open and there is no dome, only a fold-away bad-weather canopy. At La Palma, the best daytime seeing tends to occur when strong winds (5–10 m/s) from Northern directions suppress the convective plumes that arise from local ground heating. When the wind is sufficiently strong it confines the boundary convection to a thin layer of only about 10 m thickness, well below the DOT telescope height of 17 m. This extraordinary circumstance may last all day and makes La Palma intrinsically better than all US mountain sites, where good seeing occurs exclusively briefly after sunrise, before the convection starts and produces turbulence in a layer many tens of meters thick. (Comparable quality is only reached at Pic du Midi, but only after snowfall in summer which is not a yearly event.) The DOT's principle is to minimize obstruction to the local air flow and to rely on the same strong winds, blowing right through the telescope, to inhibit convective turbulence within the telescope and in its immediate surroundings.

In addition, the simple optical scheme of the DOT guarantees optimum performance by avoiding the severe alignment problems that come with more complex arrangements such as a Gregorian design. The extraordinary mechanical stability gives high pointing precision even in strong wind buffeting. The fold-away canopy survives even the severe La Palma winter storms and ice loads.

The open design of the DOT departs radically from existing solar telescopes. All current high-resolution telescopes rely on internal evacuation to avoid internal turbulence. For these, the vacuum window (in reflectors such as the NSO 76 cm VTT at Sacramento Peak, the German 70 cm VTT at Tenerife, and the French-Italian 90 cm THEMIS at Tenerife) or the objective lens (in refractors as the Swedish 47 cm SVST on La Palma) set a restrictive size limit. Thus, the DOT represents an important test for large solar telescope concepts. Also for the DOT itself. The current DOT aperture is 45 cm, but the mechanical structure accepts a 76 cm mirror without change and a 100 cm mirror with minor modification. The latter would make it the largest solar telescope in Europe and the largest high-resolution one worldwide.

2.2 Structure

The DOT is a reflector with a parabolic mirror that sits out in the open at a height of 17 m. It is located about 60 m north-west from the Swedish Vacuum Solar Telescope (SVST) at the Roque de los Muchachos Observatory, La Palma. The DOT is operated from the SVST building where the project team enjoys generous hospitality.

[1] `http://www.fys.ruu.nl/~rutten/dot/Home.html`

The primary mirror (Cervit, 45 cm diameter, focal length 200 cm) focuses the incoming beam onto a water-cooled diaphragm that reflects most of the solar image out of the telescope and transmits only a 2 by 2 arcmin subfield.

The mirror is mounted deformation-free with nine-point axial and three-point radial support in a parallactic telescope structure that is considerably overdimensioned as well as unbalanced in order to obtain extreme pointing stability. Brushless pairs of servo motors in push-pull preload configuration without backlash drive four-step gear trains achieving 1:75,000 reduction with self-aligning gears. The extreme reduction serves to drive the telescope at very low dissipation, amounting to only about 20 W, in order to avoid local heat sources.

The support tower, at a weight of 13 ton considerably lighter than the telescope itself, permits only lateral motion of the platform while inhibiting tilts. Even in strong wind buffeting the telescope therefore maintains precise tracking. The tower puts the telescope above the turbulent boundary layer especially when the strong trade wind blows upslope from Northern directions in the best-seeing weather pattern. The tower consists of open steel-tube triangles and is designed to withstand large (simultaneous) ice loads and wind pressure.

The bad-weather enclosure opens clam-like and folds away to the sides. It is made of heavy polyester fabric mounted on steel ribs and may be closed in winds up to 30 m/s (or opened, but that is less likely). When closed it should withstand the 70 m/s (Bf 12) winds that might hit Roque de los Muchachos in the harsh La Palma winter storms. The coated surface tends to remain ice-free.

2.3 Installation

The tower, platform, telescope and enclosure were all installed on the La Palma site during the summer of 1996. The primary mirror came later, after a full-size interferometer was set up at Utrecht during the spring of 1997 to construct a precise major-axis and focus defining laser system that guarantees high-precision alignment. This system has been used when the mirror and initial secondary optics were mounted during the summer of 1997.

First light took place a short while before the official First Light Ceremony on October 31, 1997. It was performed by His Royal Highness Willem-Alexander, Prince of Orange, and His Excellency Manuel Hermoso Rojas, President of the Canary Islands, in the presence of many other dignitaries including Minister J. Ritzen.

First images of outstanding quality were obtained during good seeing a few weeks later (November 26, December 5 1998; see DOT website). These were taken with simple equipment making up the STW technology-verification configuration. The prime-focus image was remagnified using relay optics including a microscope objective to obtain pixels of 0.1 arcsec and was recorded with a simple video camera. The analog signal was transported per optical link to the SVST building and there digitized with a PC, using real-time frame selection to store the best images on the PC hard disk.

2.4 Status

The completion of the DOT (at the Centrale Werkpaats of the Technical University Delft) and the installation at La Palma have been funded by a 2 Mf grant from the Stichting Technische Wetenschappen (STW). The purpose of this grant was not to provide a new solar telescope to

Dutch astronomy, but rather to test the technological innovations embedded in the telescope structure, drives, support tower, and enclosure. That phase is now over. The fact that the DOT has survived its first two La Palma winters, does not shake in strong wind buffeting, and has already produced images winning high praise from solar physicists worldwide implies that the STW grant has fulfilled its purpose. STW has made it abundantly clear that further funding for DOT utilization has to come from other sources. The DOT efforts at La Palma are therefore halted at present.

A DOT science proposal has been submitted to ASTRON (NFRA), has passed through the standard review procedure for "programmasubsidies", and has been forwarded by ASTRON to GB-E. It has been accepted by NWO on the condition that the telescope exploitation and instrumentation are funded by others. The initial tranche amounts to 600 kf during 1998–2001, with extension to 2003 depending on a 2001 review. Further details are given below, a spending profile in Table 4.

Additional funding for DOT science utilization is provided by the EC through a TMR "European Solar Magnetometry Network" that is coordinated by the DOT project scientist (Rutten). Its main goal is to perform multi-telescope campaigns in which the DOT will be combined with the other solar telescopes on the Canary Islands. The grant amounts to a three-year postdoc position plus network-related travel (plus postdocs at seven other institutions). A spending profile is added to Table 4.

The Faculteit Natuur- en Sterrenkunde (FNS) of Utrecht University (UU) has promised further support for the DOT in an initial three-year science utilization phase on the condition that NWO (GB-E) and NOVA contribute as well.

Both FNS and ASTRON have declared to be in principle willing to bridge the time gap between the urgent DOT needs and the future NOVA spending profile through pre-financing.

It is hoped that the NOVA funding for instrumentation requested here will fulfill the conditions imposed by GB-E and FNS, effectively "closing" the boundary conditions needed to start an initial three-year science phase in which the DOT viability for first-class science may be proven. This first three-year phase is detailed below, with budget specifications. All funding needs and all funding prospects for this three-year science "validation" phase are tabulated below in order to provide a complete picture. Plans for DOT instrumentation and science on a longer time scale, after the initial three-year period, are outlined briefly for completeness.

3 Plans for scientific utilization

3.1 Proxy magnetometry

The STW-funded post-focus equipment (simple video image recording) suited the purpose of technology verification, including gathering "first light" and first images, but is not fit for scientific usage at the frontier of present-day solar physics. The granulation observed in such broad-band continuum images serves very well as yardstick to judge telescope performance and local seeing characteristics, but granulation itself is an understood phenomenon that is no longer of much scientific interest.

The post-focus instrumentation that is required for the initial science program consists of three-channel proxy magnetometry as described above. Synchronous high-resolution solar imaging in these magnetic-field diagnostics represents the first goal of DOT science utilization. It aims in particular at obtaining high-resolution image sequences in conjunction with the MDI magnetograph and UV spectrometers onboard the SOHO mission and with the high-resolution UV imaging by the TRACE mission.

Thus, the initial-science program aims to use the G band, Ca II K and Hα simultaneously to chart magnetic fine structures through the photosphere and chromosphere, up to the height where the ultraviolet diagnostics from space platforms take over. This program also fits the EC-TMR network task package.

The techniques will closely follow the examples set in recent years at the Swedish Vacuum Solar Telescope (SVST). This is a vacuum refractor with the same aperture size as the DOT that has widely been acclaimed as the sharpest solar telescope sofar. The SVST team, led by Prof. G. Scharmer of Stockholm Observatory and funded by the Swedish Royal Academy of Sciences, has been and is at the forefront in developing the high-resolution techniques that the DOT will exploit. The DOT is operated from the SVST building in close cooperation with the Swedish colleagues. In fact, SVST hardware will be borrowed extensively during the DOT start-up phase. We also aim to install and use the sophisticated camera-control software that the SVST team has developed together with the Lockheed-Martin Solar and Astrophysics Laboratory (Palo Alto) over the past years.

One benefit of the close connection with the SVST is that it will be easy to operate the two telescopes simultaneously, sharing telecope and camera control across the local computer networks (Ethernet and twisted pair). The SVST developments now center on filter magnetography using liquid-crystal technology and an elaborate model of telescope polarization. This SVST program and the three-channel DOT proxy magnetometry are highly complementary, so that combined operation will benefit many observing programs.

3.2 Phase-diverse speckle restoration

High angular resolution is the science-driven main requirement for the DOT — as for most other solar telescopes excepting those used in helioseismology. The DOT's aim is to furnish image quality that is set by the non-local seeing alone, not by the telescope nor by local disturbances caused by the telescope or the support structure. The next quest is to minimize the wavefront perturbations caused by the non-local seeing. Part of the funding request in the ASTRON/GB-E DOT science proposal therefore concerned a postdoc with expertise in the new technique of phase-diverse speckle interferometry, plus a 100 kf hardware investment. As mentioned above, the technique has been demonstrated (at the SVST) but it is yet far too computer-demanding to be used in every-day observing practice. Parallel processing with DSP's (as in PuMa) or possibly even Pentium's should enable speed-up to the level that each day's data can be restoration-processed overnight. This would dramatically enhance the productivity of high-resolution observing through reaching the 0.2 arcsec diffraction limit when the seeing is just good rather than superb.

The actual NWO/GB-E allocation requires a mid-term review and break point which necessitates postponement of starting a multi-processor machine until the second tranche, after the initial three-year period. Such delay is undesirable from the solar physics point of view, for which phase-diverse speckle processing will be a boon to have from the start. A way out is to start by implementing and improving existing methods on regular workstation clusters and aim at speed-up that won't reach daily turnaround but that will permit restoration of selected best sequences, say one or two per observing campaign. The experience so gained may then be extended to a fast-turnaround hardware system in the second tranche if funded. The excellent contacts of the DOT group with phase-diverse speckle experts worldwide (Keller, von der Lühe, Löfdahl, Kneer, and their coworkers) make it a viable option to let this be undertaken by an AIO. For this reason, the AIO that is part of the NWO/GB-E grant is now tentatively scheduled as a speckle-oriented one. No need to add that it is a good investment to educate a young scientist in wavefront restoration lore.

3.3 Stokes vector magnetometry

An ASTRON feasibility study has been requested and allocated to see whether full Stokes vector magnetometry may be achieved at the DOT using a fiber image reformatter.

The DOT is particularly suited for vector magnetometry. First, it provides the required angular resolution. Second, because it is a reflector the focus is co-spatial at all wavelengths. Third, the parallactic mount, the absence of large-angle reflections and the absence of image rotation make it suited to high-precision polarimetry, without the large telescope polarization that impedes precise polarimetry at heliostat-guided telescopes. Fourth, its potentially high pointing precision permits astrometric tracking in solar coordinates which is of much interest to field migration studies. Finally, the DOT may reach very high sensitivity when its aperture is doubled in size. For these reasons the development and installation of a Stokes vector magnetograph is a natural desire on a longer time scale. It will exploit the unique DOT capabilities to their full extent. The reason to defer it until after the initial three-year science program is simply that building a Stokes magnetometer is too large a project for the present team and funding.

Stokes vector magnetometry requires spectral selection of one or more narrow bandpasses within one or more Zeeman-sensitive lines. There are various possibilities (magneto-optic resonance-cell polarimetry, liquid-crystal encoding with a tunable filter, Fabry-Perot passband selection, etc.). The preferred option is to use a classical grating spectrometer in order to employ multiple specific Zeeman lines for precise multi-variable Stokes inversion. If a fiber image reformatter (changing a 2D input field into a 1D slit aperture) indeed turns out feasible, it will not only make it possible to detach a spectrometer from the DOT prime focus structure, but it will represent an important breakthrough by permitting 2D instantaneous spectrometry. This is very important because instantaneous registration of full isoplanatic patches enables phase-diverse speckle restoration per spectral resolution element, in principle permitting precise Stokes vector magnetometry at the telescope diffraction limit when the seeing is just good. The main issue is whether sufficiently thin fibers can be used to maintain full angular resolution without too much loss in étendu.

However, even if the fiber reformatter feasibility study results in green light, this project will be timelined after the initial three-year period and require separate proposals. The same holds for a DOT aperture upgrade.

3.4 International aspects

The DOT project is a Dutch enterprise so far, but it is likely that the existing collaborations with teams elsewhere will expand and that foreign colleagues will also become DOT users.

The most intensive collaboration is with the SVST team of the Swedish Royal Academy of Sciences (KVA). Prof. Scharmer and his team have not only received the DOT team in their building with very generous hospitality, but also contribute extensive equipment on loan (estimated value 100 kf) and have no objection against sharing their very considerable investments in data acquisition software. The science cooperation will intensify, also through the EC-TMR grant. A Utrecht student (Rouppe van der Voort) is now graduate student at Stockholm; more may follow. Rutten and Kiselman (KVA) are formally part of a NASA-funded program with Berger (Lockheed-Martin) on G-band formation. The KVA group has about the same size as the DOT group will have in the proposed three-year program — each small enough that intensive cooperation is a boon to each.

Other contributions in kind consist of the highly valuable Hα filter on indefinite loan from the Canadian Research Council (estimated value 200 kf), and the ANA software system for advanced image processing from Lockheed-Martin (15 manyears of effort). The latter group is a frequent user of the SVST, operates SOI/MDI on SOHO as well as TRACE, and has close connections to the Utrecht group — AIO Hagenaar spends half her time at Palo Alto, and three Utrecht-educated solar physicists hold or will hold positions there (Schrijver, Martens, Strous). The group has also given permission to mount the SOUP campaignwise at the DOT. The SOUP is a versatile rapidly tunable filter, developed by NASA at megadollar cost, that has been the backbone of many Lockheed-Martin campaigns at the SVST. It was developed for space platforms and has flown in the Spacelab 2 mission. Installing the SOUP requires a more involved optical scheme (deflected beam through the hole in the primary mirror to a Cassegrain-like focus) which may possibly be realized towards the end of the three-year program.

The US National Solar Observatory (NSO) is currently undertaking design studies towards a new large US solar physics facility. The current concept ("CLEAR") aims at a 4 m telescope with DOT-like characteristics, combining a non-vacuum telescope with active mirror flushing. The NSO director (J.M. Beckers) has proposed to use the DOT for technology and principle tests, and has started to search funding to do so.

On a longer time scale it appears likely that the DOT may figure in adaptive-optics technology tests for larger future facilities in Europe. The international LEST project which aimed to put a 2.5 m solar telescope on La Palma has finally been definitely terminated, mainly due to lack of funding. New initiatives are being taken to start an adaptive optics program that initially center on technology demonstration. The initial science validation should increase the DOT viability to partnership in such programs.

Finally, the Abteilung Planetforschung of the Deutsche Luft- und Raumfahrt laboratory at Berlin has expressed interest to use the DOT for exact position determination of asteroids and comets. An optical design study has shown that this is feasible with a 76 cm mirror using daytime instrumentation and nighttime instrumentation in separate beam-switched foci. The DLR group has embarked on searching funds for the required mirror replacement.

4 Three-year initial-science program

The three-year initial-science program detailed below consists of:

(i) – installation of three-channel proxy-magnetometry filter imaging (G band, Ca II K and tunable Hα);

(ii) – observations with the above, especially in concert with SOHO, TRACE, and/or other Canary Island telescopes;

(iii) – software development of phase-diverse speckle restoration.

Other plans (fiber reformatter, Stokes magnetometer, near-real-time phase-diverse speckle processor, larger aperture, adaptive optics experiments) are in principle deferred to a second tranche subject to review, or to separate project proposals.

4.1 Technical aspects

Realization of the requested three-channel imaging for proxy magnetometry is relatively straightforward. The design of the required secondary optics is complete. The required spectral bandwidths are 1 nm for the G-band, 0.3 nm for Ca II K, and 0.02 nm for Hα. The first two require simple interference filters, but we may prefer to employ a narrower-band Ca II K filter in our possession for studies that accept longer exposure times. The Hα bandwidth must not only be narrow but also be rapidly tunable. The DOT team has a high-quality Hα Lyot filter on indefinite loan from the Canadian Research Council that was earlier employed at the Ottawa River Solar Observatory. It will be refurbished and mounted besides the incoming beam, where also the Ca II K channel will be located. The long exposure times needed for the narrow passband necessitate a fast tip-tilt correlation tracker that compensates for image motion by steadying the granulation pattern, nowadays a standard technique at solar telescopes.

In addition to these filters, the three-channel program requires secondary optics that is optimized for each wavelength, large-format digital CCD cameras of good quality, digital optical fiber links to the computers in the SVST building, fast interfaces that can access the large data streams, and fast processors for real-time frame selection and storage. In these aspects we intend to closely follow the SVST example — and gratefully accept the Swedish offer to borrow some of their hardware temporarily while ordering or awaiting our own.

The preferred CCD cameras are Kodak Megaplus units. They have become the workhorse at most solar telescopes due to their reliability and exceptionally clean chips. They are available in a variety of pixel formats (up to 4K $\times$ 4K), bit resolution (8 or 10), and chip cleanliness levels, at prices that range from a few 10 kf to far over 100 kf. We aim to buy these (or comparable other cameras if they appear on the market) one by one in delayed succession, using older cameras (8 bits, 1.3 million pixels) on loan from the SVST as long as feasible. Operation at the Ca II K wavelength requires lumigen coating.

The preferred computer processing will employ DEC-Alpha workstations, again partially relying on SVST sharing. The Swedish group is involved in a formal collaboration with Digital Equipment in which fast interfaces ("Pamette") have been developed that permit handling large-format CCD cameras at exceptionally high speeds, with data transfers over 100 Mbyte/s. The digital data link between the DOT-mounted cameras and the computers located in the SVST building will use optical fiber technology.

The optical hardware that is required for phase-diverse speckle restoration consists of beam splitters to be mounted before each CCD camera, dividing each field into two halves that are synchronously exposed and provide wavefront sampling in focus and out of focus. No other hardware is required for the initial software development and slow-turnaround phase. The multi-processor array (DSP's, Pentium's or possibly Alpha-technology boards) needed for fast turn-around is tentatively part of the second tranche of the NWO/GB-E grant. The main overall effort is in software and will heavily rely on cooperation with experts abroad, partially through the EC-TMR network.

Finally, an elaborate software model will be developed that describes the telescope pointing drifts including thermal effects (such as due to uneven irradiation of the tower legs). It will be fine-tuned using the tracker signal and eventually provide astrometric solar-feature pointing that even includes solar differential rotation — scientifically worthwhile because it will permit magnetic field migration studies in fixed solar-rotation reference frames.

4.2 Funding needs for instrumentation and exploitation

Table 1: Personnel costs. Column labeled Gross/year: gross salaries per year in kf. The last column sums these over the three-year program. Pro memorie items: permanent staff. Bracketed entries: funding already allocated (NWO/GB-E on the condition that the three-year program is realized). Other entries: funding requested from NOVA and the Utrecht Faculteit Natuur- en Sterrenkunde (FNS). SIU: Sterrekundig Instituut Utrecht (part of FNS). IGF: Instrumentele Groep Fysica (workshop FNS).

Task	Type/person	Gross/year	Gross/3 years
Instrumentation	60% Hammerschlag (SIU)	pm	pm
	20% van der Zalm (SIU)	pm	pm
	engineer	72	220
	mechanic	53	159
	IGF 1.5 my/yr	126	378
	total	251+pm	759+pm
Science	60% Rutten (SIU)	pm	pm
	SIU AIO	[50]	[150]
	NWO/GB-E postdoc	[80]	[240]
	NWO/GB-E AIO (speckle)	[50]	[150]
	EC-TMR postdoc	[80]	[240]
	total	[260]+pm	[780]+pm

4.2.1 Personnel

Table 1 lists *all* manpower efforts for the three-year initial science program, except trainees (stagiaires), undergraduate students and local La Palma manpower hired per hour. The table is complete through including both open posts (specified in kf per year and summed over three years, respectively) and salaries that are already covered by the Sterrekundig Instituut Utrecht (SIU, entered pm) or the NWO/GB-E and EC-TMR grants (entered between brackets).

The DOT core team that installed the DOT at La Palma consisted of Hammerschlag (DOT designer and project manager, SIU), Bettonvil (engineer, STW) and Hoogendoorn (mechanic, SIU), with considerable assistance from the FNS workshop (IGF), the Central Workshop of TU Delft where the DOT was assembled, and a large amount of manpower furnished by technology trainees (stagiaires) from technical schools around Utrecht who spent hard-working vacations at La Palma in exchange for travel and lodging plus f 200/week.

Hammerschlag and Rutten (DOT project scientist, SIU) are full-time involved with the DOT except for their teaching obligation, officially set at 40% of their official work hours (the part for which they are employed by the Julius Instituut rather than the SIU).

SIU programmer Van der Zalm is allotted to the DOT for 20% of his time, corresponding to the DOT-oriented SIU staff fraction.

Bettonvil's employment by STW ends June 30, 1998. Hoogendoorn is being transfered from the SIU to the IGF as part of an SIU budget cut. Continuation of their roles is a must to continue the project. Hence, an engineer and a mechanic are entered in Table 1 at the current salaries of Bettonvil and Hoogendoorn, respectively.

The IGF entries specify manpower from the FNS workshop. They do not include a f 200/man-week bonus required by the IGF for work at La Palma.

The AIO listed as SIU is one of the four AIO's allotted by the FNS to the SIU and allotted by the SIU to solar physics. The current occupant is Mrs. Hagenaar who will defend her thesis (on magnetic patterning over the solar surface, a DOT science topic) next year.

The NWO/GB-E and EC-TMR grantees (postdocs and AIO) will be full-time DOT-involved except for education and teaching obligations (AIO). As mentioned above, the NWO/GB-E AIO will be probably be instrumentation-oriented by being put to phase-diverse speckle restoration, but is here tabulated under Science — it is a matter of argument where such a thesis belongs but it will be supervised by Rutten anyhow.

Table 2: Material costs of the three-year initial science program, excluding telescope exploitation. Two CCD cameras are entered between brackets in the hope to use older ones on loan from the SVST.

Description	1998	1999	2000	2001	Total over 3 years
Mechanical	10	20	20	10	60
Optics	50	50	50	–	150
CCD cameras and controllers	–	80	[80]	[80]	[160]+80
Data links, interfaces	–	20	20	–	40
Computers	10	30	20	–	60
Total	70	200	[80]+110	[80]+10	[160]+390

4.2.2 Materials

Table 2 specifies all material costs for the three-year initial program, with spending profiles. All items concern the realization of the three-channel secondary optics and image acquisition. The item "Mechanical" comprises raw materials for component fabrication as well as purchase of standard components (bearings, slides, lens mounts). The optical components are mostly lenses and beam splitter cubes that require special fabrication due to the very tight tolerances set by the need to maintain the telescope diffraction limit throughout the light path. Lenses and beam splitters of this quality tend to be 10 kf apiece.

We have targeted the Megaplus cameras from the current Kodak catalog at 10 bits, class II (second rate but yet good) and $2K \times 2K$ as best value/cost choice at present, at 80 kf a piece. Ideally, we would purchase three of these right at the start, but their high price makes this a desire that is hard to realize. Fortunately, we have been promised the use of older Megaplus camera units in the possession of the SVST team when these are replaced by new $2K \times 2K$ ones now on order. The old ones cover only a smaller field (1.3 million pixels) and have an increased risk of malfunctioning (Megaplus shutters tend to break down after a few million cycles). Nevertheless, we have taken the Swedish offer gratefully for granted and have therefore added two of the three units as pm (bracketed).

The data links, interfaces and computers are also pursued in collaboration with the SVST team, to some extent profiting from their direct collaboration with DEC.

Table 3: Yearly DOT exploitation costs. CCI: international steering committee of the Roque de los Muchachos Observatory (RdlM). IAC: Instituto de Astrofísica de Canarias. SVST: Swedish Vacuum Solar Telescope. KVA: Swedish Royal Academy of Sciences.

Item	kf/yr
CCI contribution RdlM User Institute (set by the IAC)	25
SVST (KVA) water, power, etc	10
Telephone, fax, copier	10
Insurances	5
Local manpower	30
Telescope control systems	40
Construction materials	25
Maintenance, winter protection	30
Travel	100
IAC 0.5 postdoc (3 Mpts)	pm
Total	275

4.2.3 Exploitation

The projected DOT exploitation costs per year are specified in Table 3. The height of the first item (CCI User Institute contribution) is set by the Spanish authorities (the IAC at La Laguna) with an intransparent formula including facility area. The SVST colleagues do not ask rent for the use of their building but are satisfied with pro-rata sharing of the daily costs. Local manpower consists of services from SVST personnel and local Spanish manpower paid on an hourly basis, including local installation, power and network connections, computer maintenance, site construction and management, customs handling, materials transport, secretarial and interpreter services, etc.

Telescope control encompasses the motors, drive trains, positioning system, guider system, control links, control electronics and position control computer. Construction materials are bolts, paint, elevator hardware, electric equipment, water cooling equipment, etc.

The travel budget listed here only concerns the instrumentation efforts by the DOT core team, IGF personnel and traineeships (stagiaires) but no science utilization. The amount seems large but isn't, see Section 4.2.4 below.

The pm post at the bottom of Table 3 is proposed by IAC Director Fr. Sanchez as an opening bid for future negotiations on a Memorandum of Understanding concerning the DOT. It is a new incarnation of an old issue that triggered considerable debate in the past but blew over in the end. Originally, Sanchez required foreign users of the La Palma site to supply funding for

Spanish postdocs at their user home institutes. Nowadays he wants funding for IAC personnel at La Laguna. The negotiations are further complicated by his desire to have a formal treaty with the Netherlands at the Foreign Affairs level, whereas NWO (GB-E) has signalled that a low-level DOT Memorandum signed by Utrecht University is to be preferred. One bargaining element is that the IAC already receives a full three-year postdoc position thanks to the DOT through Rutten's efforts in cornering the EC-TMR grant. A fall-back (but undesirable) financial guarantee in this negotiation consists of the rotating AIO-ship assigned to solar physics by the SIU. The item is left open here.

4.2.4 Travel

Since travel to La Palma is an important budget item both in exploitation and in science utilization, further specification is warranted. All DOT travel to La Palma is based on the following principles:

- flights: use weekly charters wherever possible, otherwise the cheap restricted rates that Transavia and Iberia offer via Tenerife;
- La Palma transportation: two DOT cars, one funded by STW and one Hammerschlag's private property, are used for all local transport;
- stays: since the Residencia is far too expensive for extended stays, the DOT team rents small houses in the nearest hamlet (Las Tricias, to the west of Roque de los Muchachos).

Experience has shown that the average cost of a return trip is f 1000 while the daily cost of living including rents, car maintenance, cleaning and evening meals at the Residencia averages to f 100/day per person. This is far below the cost of full board at the Residencia. The penalty is the need for daily travel up and down the mountain, a scary 50 min drive from Las Tricias. However, a car would be needed even when staying at the Residencia.

A three-week stay for one person costs 3 kf on average. Typical three-week installation campaigns by the instrumentation team (Hammerschlag, Bettonvil, Hoogendoorn, IGF technician, trainee) last year took 15 kf on average. The instrumentation part alone therefore adds up to the 100 kf listed in Table 3. The science-part travel will largely be funded from the NWO/GB-E and EC-TMR grants. The SIU has allotted half of its total yearly travel budget to the DOT.

4.3 Spending profiles

The spending profiles and budget distributions for the science grants are specified in Table 4.

The EC-TMR overhead entries are estimates of what may be left to spend after UU and FNS have taken their toll, but they are also a safeguard against ECU/f inflation and remain therefore uncertain.

The DOT allocations from the yearly SIU budget are also listed, including 1998 as a full year and therefore leaving 2001 open to cover the same three-year extent as for all other table entries. Each SIU travel entry (15 kf) is half of the yearly SIU travel budget. The computer entry represents 10–20% of the SIU computer budget, depending on budget cuts and other uncertainties. The exploitation entry is over a quarter of the total remaining SIU exploitation budget.

The last lines sum the travel and materials/computers/exploitation entries over the three sources, adding the EC-TMR overheads to the latter. The travel parts of the NWO/GB-E and EC-TMR grants concern science travel exclusively. The EC-TMR budget may officially be used only for travel to Network partners, but the SVST from which the DOT is operated is one of those.

The 15 kf/year SIU allocation may serve both the science and the instrumentation parts of the three-year program. Unfortunately, there is no fund to send students to La Palma.

Table 4: Spending profiles and budget distributions for the science grants and the non-personnel SIU contributions. All entries in kf. The last column sums the yearly entries, effectively over three years duration.

Source	Item	1998	1999	2000	2001	Total
NWO/GB-E	Postdoc	40	80	80	40	240
	AIO	20	50	50	50	170
	Travel	10	40	40	10	100
	Materials	30	30	30	–	90
	Total	100	200	200	100	600
EC-TMR	Postdoc	40	80	80	40	240
	Travel	7	14	14	14	49
	Consumables	–	2	1	1	4
	Overhead	3	6	6	3	18
	Total	50	102	101	58	311
SIU	Travel	15	15	15	–	45
	Computers	10	10	10	–	30
	Other exploitation	42	42	42	–	126
	Total	67	67	67	–	201
Total travel		32	69	69	24	209
Total materials, computers, exploitation		85	90	89	4	268

4.4 Funding request

Tables 1–3 show what is needed for the three-year DOT science program. The personnel costs needed for the instrumentation are specified by the non-bracketed entries in Table 1. Table 2 specifies the material needs, with two of the three CCD cameras bracketed out by relying on old SVST hardware. Table 3 specifies the yearly exploitation costs.

Table 4 shows what is in principle available from the science-part grants (NWO/GB-E and EC-TMR) and the yearly SIU budget. The science grants together furnish a team large enough to indeed produce science as is needed to prove the DOT science viability. They also furnish travel funds that are roughly sufficient to execute the science observations. In addition they furnish some hardware money.

It is very obvious that the problem is with the instrumentation part. The materials items furnished by the science grants and the — already large share — of the SIU budget are clearly insufficient, by a long way, to cover the instrumentation and exploitation costs for the three-year program.

As DOT project scientist and DOT project manager, respectively, we request NOVA to support the DOT instrumentation for the three-year science validation phase with a sizable contribution — sizable enough to produce closure of the boundary conditions imposed by NWO/GB-E and FNS (Section 2.4).

By doing so, NOVA will sustain the largest current instrumentation project in Dutch university astronomy — one that has gained credibility with the superb first images that followed so soon after the first light ceremony last autumn.