

Aperture Increase Options for the Dutch Open Telescope

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Abstract. This paper is an invitation to the international community to participate in the usage and a substantial upgrade of the Dutch Open Telescope on La Palma (DOT, <http://dot.astro.uu.nl>).

We first give a brief overview of the approach, design, and current science capabilities of the DOT. It became a successful 0.2-arcsec-resolution solar movie producer through its combination of (i) an excellent site, (ii) effective wind flushing through the fully open design and construction of both the 45-cm telescope and the 15-m support tower, (iii) special designs which produce extraordinary pointing stability of the tower, equatorial mount, and telescope, (iv) simple and excellent optics with minimum wavefront distortion, and (v) large-volume speckle reconstruction including narrow-band processing. The DOT's multi-camera multi-wavelength speckle imaging system samples the solar photosphere and chromosphere simultaneously in various optical continua, the G band, Ca II H (tunable throughout the blue wing), and H α (tunable throughout the line). The resulting DOT data sets are all public. The DOT database (<http://dotdb.phys.uu.nl/DOT>) now contains many tomographic image sequences with 0.2-0.3 arcsec resolution and up to multi-hour duration. You are welcome to pull them over for analysis.

The main part of this contribution outlines DOT upgrade designs implementing larger aperture. The motivation for aperture increase is the recognition that optical solar physics needs the substantially larger telescope apertures that became useful with the advent of adaptive optics and viable through the DOT's open principle, both for photospheric polarimetry at high resolution and high sensitivity and for chromospheric fine-structure diagnosis at high cadence and full spectral sampling.

Our upgrade designs for the DOT are presented in an incremental sequence of five options of which the simplest (Option I) achieves 1.4 m aperture using the present tower, mount, fold-away canopy, and multi-wavelength speckle imaging and processing systems. The most advanced (Option V) offers unblocked 2.5 m aperture in an off-axis design with a large canopy, a wide 30-m high support tower, and image transfer to a groundbased optics lab for advanced instrumentation. All five designs employ adaptive optics. The important advantages of fully open, wind-transparent and wind-flushed structure, polarimetric constancy, and absence of primary-image rotation remain. All designs are relatively cheap through re-using as much of the existing DOT hardware as possible.

Realization of an upgrade requires external partnership(s). This report about DOT upgrade options therefore serves also as initial documentation for potential partners.

1. Introduction

During the late 1990s the Dutch Open Telescope (DOT, Fig. 1 and <http://dot.astro.uu.nl>) was the pioneering demonstrator of the open-telescope technology now pursued in the German GREGOR and BBSO NST projects and inspirational to the US ATST project. These projects capitalize on the advances in wavefront restoration through adaptive optics (AO) and numerical image processing which now enable meter-class image sharpness, far beyond the best Fried-parameter values at any site, and so require telescope technology beyond the 1-m evacuated-telescope technology limit realized by the Swedish 1-m Solar Telescope (SST). In the meantime the 45-cm DOT became an outstanding supplier of solar-atmosphere movies sampling the photosphere and chromosphere simultaneously at up to 0.2 arcsec resolution (Section 2). The resulting image sequences are publicly available for analysis (Section 3).

The major science drivers for aperture increase beyond the SST are:

1. *Photosphere*: precise, deep, and complete Stokes polarimetry at high angular resolution, preferably combining visible and infrared lines in 2-D mapping. Targets: umbrae, penumbrae, pores, plage and network magnetic elements, internetwork fields, etc.
2. *Chromosphere*: high to very high cadence profile-sampled narrow-band imaging in chromospheric lines, in particular Ca II H&K with spectral sampling throughout the extended line wings in order to follow dynamic phenomena with height throughout the upper photosphere and low chromosphere, and the Ca II infrared lines and the Balmer lines with full profile mapping in order to disentangle the complex opacity, source function, and Doppler sensitivities that make the chromosphere such a rich scene in these lines. Targets: filaments, active regions, mottles/fibrils/spicules, Ellerman bombs, flares, wave patterns, shock dynamics, etc.

For both, sufficient photon collection is the principal large-aperture motivation. To freeze the seeing no exposure should exceed 10 ms, also for narrow-band diagnostics. Multi-frame image collection for MOMFBD restoration (van Noort et al. 2005) or many-frame collection for speckle reconstruction must be completed within the solar-change time per resolution element, including spectral profile sampling as necessary. The change time becomes shorter for larger angular resolution and can be much shorter than the sound-speed crossing time, as demonstrated by the recent 1-s-cadence H α movies of van Noort & Rouppe van der Voort (2006).

These science motivations plus the fact that the 50-cm SOT onboard Hinode duplicates many current DOT capabilities at a much higher duty cycle (no bad seeing, no bad weather, no nights during its non-eclipse seasons) led us to the larger-aperture designs discussed below. In Section 4 we outline how conversion of the 45-cm DOT into a larger solar telescope is not only feasible but actually a relatively cheap venue to meter-class angular resolution through using existing parts where possible. We focus on 1.4-m and 2.5-m strawman designs in a sequence of options ranging from minimum cost to maximum science capability.

We cannot realize such DOT upgrades on our own; they require external support. At present the DOT is run on a budget of about 250 kEuro/year covering salaries (excluding the first and last author who are academic staff), travel

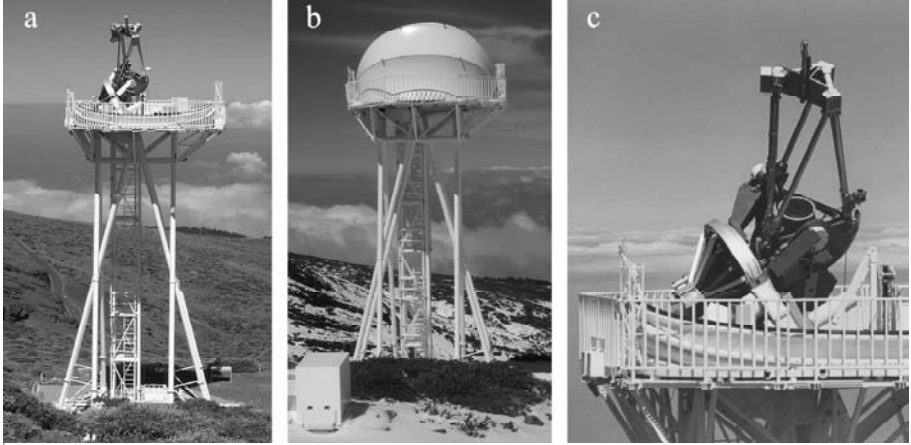


Figure 1. The existing DOT with 45-cm primary mirror at 2350 m altitude on La Palma.

(a) The DOT in operation. The 15-m tower and the telescope are sufficiently transparent to not disturb the wind which maintains temperature homogeneity in and around the telescope. At sufficient wind strength (7 km/h can be enough depending on the wind direction) the larger temperature fluctuations occurring near ground level do not reach the telescope. The special tower geometry keeps the platform parallel to the ground even under strong wind loads. The clam-shell canopy is opened completely for observations.

(b) When not in operation the telescope is protected by closing the folding canopy. It is made of strong tensioned polyester cloth with an outer PVDF coating on which snow and ice do not stick. The canopy can be opened and closed within a few minutes in winds up to 100 km/h. When closed it can withstand much stronger winds, and has already survived storms of 200 km/h.

(c) The telescope close-up. The primary mirror and the optical beam to the primary focus are fully open to wind. The DOT was the first telescope showing that such an open air path can permit diffraction-limited resolution. Note that the primary mirror is located well above the declination axis of the equatorial mount. It sticks out high above the platform into full wind flushing.

to La Palma and equipment, plus an additional allocation of up to 3000 man-hours/year of Utrecht University workshop effort encompassing mechanical design and fabrication as well as electronics and software development in very close collaboration with the DOT team. Our present funding covers these costs up to 2008, but not beyond that date while a larger budget is required to realize and operate a larger telescope (Section 5). This paper is therefore intended as initial documentation for potential partners.

2. DOT Technical Overview

The DOT performs so well thanks to the combination of (i) its wind-swept oceanic mountain site at the Observatorio del Roque de los Muchachos on the Canary Island La Palma, (ii) minimum obstruction to the wind by the very open tower, the very open telescope, and the fully-folding canopy, (iii) effective

wind-flushing of the open telescope, (*iv*) short-exposure speckle imaging, and (*v*) the consistent application of speckle restoration in an on-site processor farm.

The DOT design and construction are characterized by rigorous adherence to its open principle and large emphasis on mechanical stability. The open tower, fold-away canopy, and equatorial telescope mount are highly transparent to the fairly laminar Northern trade winds that bring the best seeing at the Roque de los Muchachos. They don't spoil the seeing; in addition, the wind flushes the telescope interior faster than internal turbulence can develop. The remaining higher-layer wavefront aberrations are corrected through speckle processing. Its advantages are that it restores the full field of observation in equal measure and that it delivers rather good results already at relatively poor seeing. It requires a large amount of post-processing but this has been remedied with the parallel DOT Speckle Processor in a nearby building. The complete system delivers 0.2 arcsec diffraction-limited image quality whenever the seeing is reasonable, already at Fried-parameter values of order 6-10 cm. At La Palma such seeing sometimes occurs during multiple hours.

During the past years the DOT has been equipped with an elaborate multi-wavelength imaging system harboring six identical speckle cameras that register wide-band continua in the blue and red, the G band at 4305 Å, Ca I H with an interference filter that can be tuned per speckle burst through the blue line wing, and narrow-band H α using a 250 mÅ FWHM Lyot filter that can also be tuned per speckle burst. Two-channel speckle reconstruction following Keller & von der Lühe (1992) permits the registration of multi-wavelength H α movies at 20-30 s cadence or single-wavelength H α movies at much faster cadence.

The DOT is usually manned from early spring until late autumn, usually with the first author taking care of the telescope operation and P. Sütterlin in control of all observing and speckle processing. A typical two-week campaign delivers on average 5-6 days with good data. Thanks to the parallel processing the data now become available soon after the campaign.

More detail is given in Hammerschlag (1981) for the original DOT design description, Rutten et al. (2004a, 2004b) for general overviews, Hammerschlag et al. (2006a) for the tower design, Bettonvil et al. (2006) for the multi-wavelength imaging, Snik et al. (2007) for ongoing work on Ba II 4554 polarimetry, and Bettonvil et al. (2004) for an earlier description of a DOT upgrade to 1.4 m aperture. All DOT papers are available at <http://dot.astro.uu.nl>.

3. DOT Database

All DOT data are public. The DOT has collected high-resolution movies of the sun since the autumn of 1999 in an increasing number of spectral diagnostics. The yearly harvest increased markedly in 2005 with the advent of the large-volume parallel DOT Speckle Processor. The DOT database resides at ftp site <ftp://dotdb.phys.uu.nl/> and has a user-friendly graphical interface at <http://dotdb.phys.uu.nl/DOT/> which for every day with worthwhile data serves a thumbnail pictorial index of what was collected. It also specifies the target, observing mode, time of observation, cadence, solar disk location, average seeing quality (Fried parameter r_0), a link to the pertinent Mees active region map, a burst-by-burst plot of the Fried parameter, and a "Get data" link to the

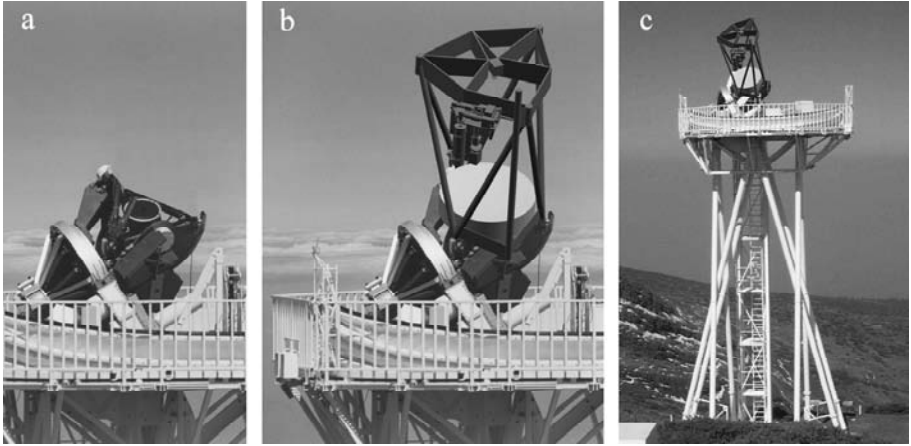


Figure 2. Option I: DOT upgrade to 1.4-m aperture.

(a) Remove the existing telescope top.

(b) Place a new mirror with a new mirror support on the existing equatorial mount, add a new telescope top, relocate the existing multi-channel imaging system to its side, and add a new prime-focus optics package. The optical scheme is shown in Fig. 3.

(c) The result – in observing position – on top of the existing tower. At a focal length of $f = 2.3$ m the telescope can still be parked within the existing 7-m canopy.

corresponding directory in the DOT database. The basic DOT data product consists of FITS files per speckle-reconstructed image, but for many runs the data base also serves processed and aligned image sequences as data cubes.

You are welcome to use any DOT data for detailed analysis. Explanation and IDL reading instruction is given under “DOT data” at <http://dot.astro.uu.nl>. Questions should go to P.Suetterlin@astro.uu.nl.

We plan to integrate the DOT data base into the Virtual Solar Observatory (<http://sdac.virtualsolar.org>) and to add more search capability as well as other user commodities.

4. DOT Upgrade Designs

In the remainder of this contribution we present a range of options to increase the DOT aperture to meterclass size, in order of increasing gain in science capability and cost.

4.1. Option I: upgrade to 1.4-m aperture

The simplest, Option I, is to upgrade the existing DOT with 45-cm primary mirror shown in Fig. 1 to 1.4-m aperture by removing the existing telescope top, placing a new mirror support with a new 1.4-m mirror with focal length $f = 2.3$ m (opening ratio $f/1.64$) on the existing telescope mount, adding a new prime-focus optics package (secondary parabolic mirror, two flat mirrors

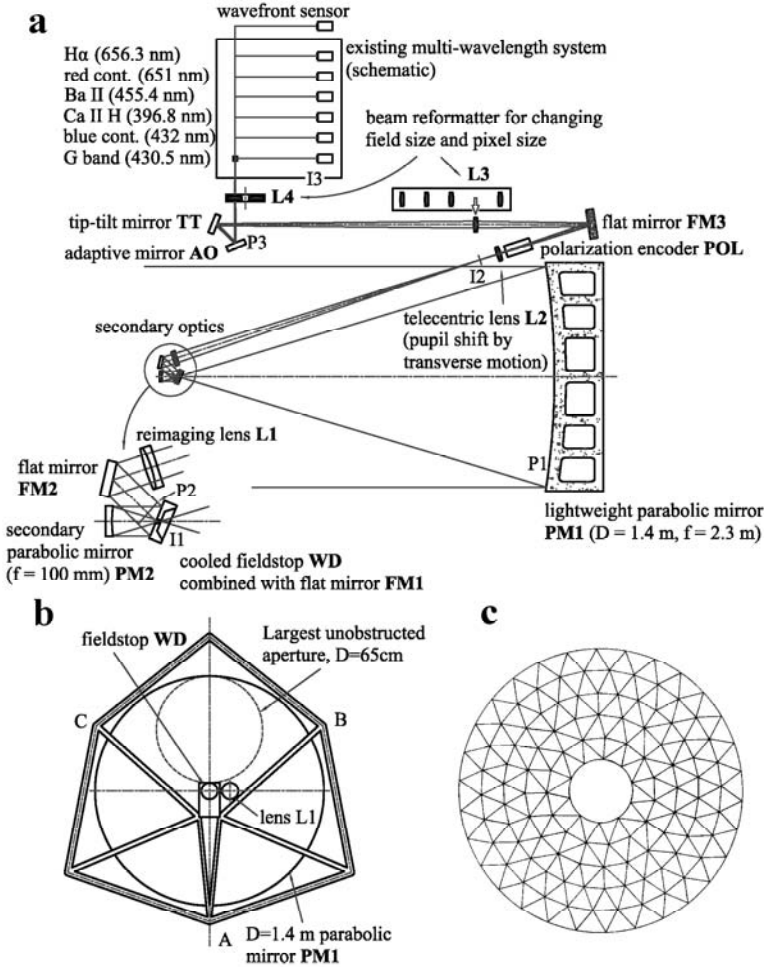


Figure 3. Optical layout of Option I with 1.4-m primary mirror. (a) Side view. The parabolic primary and secondary mirror together are coma-free to produce diffraction-limited quality over the full field of view. L1 produces an enlarged image I2 near the field lens L2. The ensembles of interchangeable lenses L3 and L4 produce user-selectable choice between angular resolution and field size whereas transverse translation of telecentric field lens L2 offers transversal pupil shift. (b) Top view of the aperture = primary mirror with spider shadow. Transversal pupil shift allows obstruction-free apertures up to 65 cm (circle in the upper part). The inclined flat mirrors FM1 and FM2 reflect the light in perpendicular directions to compensate partial polarization. (c) Alternative spider design using very thin plates gradually spreading in all directions to obtain a diffraction pattern without pronounced ghosts. Such spider geometry can be optimized together with the AO layout.

and re-imaging lens) and adaptive optics, and constructing a new telescope-top support structure (Figs. 2 and 3). Re-used are the existing tower, the platform, the folding canopy, the equatorial mount, the multi-wavelength imaging system, and the image acquisition and processing computers in the nearby SST and Automatic Transit Circle (ATC) buildings. We call this simplest and cheapest upgrade Option I here. It was called DOT⁺⁺ in a proposal detailed in Bettonvil et al. (2004) and is summarized here.

The optical layout is shown in Fig. 3. Both the primary and secondary mirrors are parabolic because two parabolic mirrors in cascade leave no coma, making the whole field diffraction limited. The two 20° inclined flat mirrors FM1 and FM2 reflect in mutually perpendicular directions compensating their partial polarization. The layout includes a tip-tilt mirror and an adaptive-optics mirror. The spider construction may be optimized commensurate with the AO pupil geometry (Fig. 3c).

This optical design permits a flexible near-instantaneous user choice between angular resolution and field size, achieved with the sets of interchangeable “zoom-out” lenses L3 and L4 and maintaining the photon flux per pixel. Transversal pupil shift is possible through translation of telecentric field lens L2 and enables selection of obstruction-free apertures up to 65 cm. See Bettonvil et al. (2004) for detail.

An advantage of the equatorial mount is that there are no image rotations relative to the AO-system for the optics system on the pointed telescope structure. Combination of AO with post-detection numerical wavefront restoration is possible and desirable.

4.2. Option II: upgrade to 2.5-m aperture

The existing canopy has a diameter of 7 m which limits the focal length of the primary mirror to 2.3 m. This limits the aperture diameter to 1.4 m because a faster opening ratio brings too severe optical and thermal problems.

However, the existing equatorial DOT telescope mount and drives are sufficiently stable, stiff, and large to harbor a 2.5 m diameter mirror with appropriate mirror support and prime-focus support structures without modification. Fig. 4 shows photographs of the extraordinary stable DOT mount and gears. They were considerably overdimensioned in the original design to ensure strict rigidity and enable the option of installing a larger mirror later. The equatorial mount has a declination gear wheel with pitch circle diameter 174 cm, pitch 2.5 cm and teeth width 7 cm and an hour-angle gear wheel with pitch circle 190 cm, pitch 3.1 cm and teeth width 11 cm. The DOT drives are not only overdimensioned but also employ self-aligning pinions invented, developed, and tested during the DOT construction. Their principle is illustrated in Fig. 4d; more details are given in Hammerschlag (1983). These pinions achieve line contact between meshing teeth over the whole tooth width under typical telescope loads. The latter are small compared with standard mechanical practice. Under such small loads teeth contact in classical drives occurs only over a part of the tooth width, reducing the structural stiffness. Large preloads are no remedy since they would produce stick-slip irregularities in the very slow motion needed to follow targets. These self-aligning pinions turned out to work exceptionally well, so that

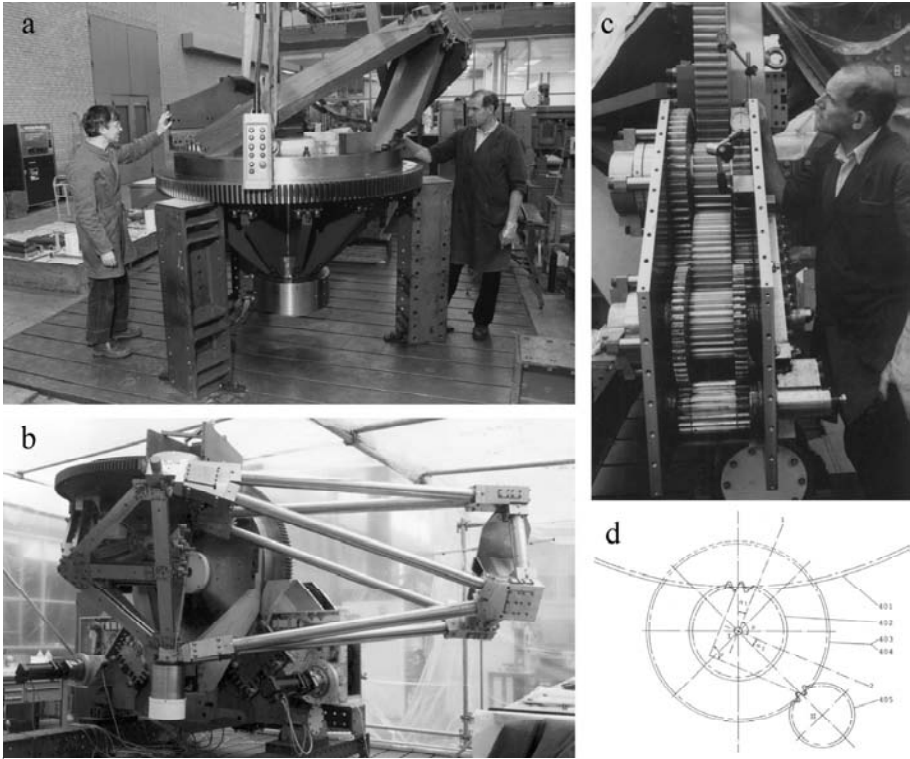


Figure 4. Fabrication of the exceedingly stable DOT mount and drives.

(a) Hour-angle gear wheel (190 cm diameter) with above the teeth the roller raceway for the radial support. The fork is in construction above the raceway. Below, near the floor, is the large double-row spherical roller bearing which was custom-made by SKF to minimize clearance. It has a large central hole to permit beam passage to an optional optics lab.

(b) The mount and drives fully assembled in the workshop, with the hour-angle axis oriented horizontally. The mount permits pointing in all directions.

(c) One of the two hour-angle gears. All gears have self-aligning pinions. This special design, a DOT invention to minimize the risk of stick-slip, achieves line contact between the meshing teeth over the whole tooth width even under the relatively small loads used here.

(d) Principle of the self-aligning pinions. On both sides of a pinion is a gear of the next stage. This pair of gears is fixed with a ring of screws to the pinion. It forms a single block, which is supported by a single double-row spherical roller bearing. This bearing permits rotation around three axes: the normal rotation around axis I perpendicular to the drawing plane, and two perpendicular axes 1 and 2 in the plane of the drawing. Rotations of the block around axis 1 provide line contact of the pinion with the large gear wheel whereas rotation around axis 2 provides line contact between the gears of the next stage (pinion II). The two half parts of the next gear were ground together for optimum matching.

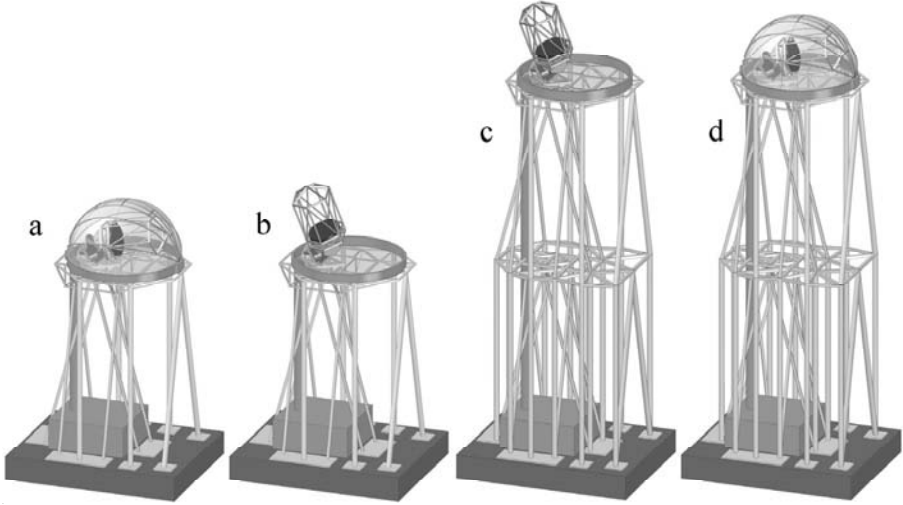


Figure 5. Options II and III with 2.5-m primary mirror.
 (a) Option II: enlarged 15-m tower and platform, carrying 9 m canopy with 2.5-m mirror on the existing mount.
 (b) Option II with open canopy and telescope in operating position.
 (c) Option III: the Option II tower with platform, telescope and canopy put on top of an secondary base structure of 15-m height, bringing the telescope to 30 m above the ground. The added base structure also has a geometry which maintains parallel motion of the platform relative to the ground under varying wind loads. Such parallel motion combines well with the geometry of the upper tower with separated base points of the triangles (see text for further explanation).
 (d) Option III with telescope in parked position and closed canopy.

the gears are actually much stiffer than the design tolerance of deformations ≤ 0.07 arcsec at wind speeds 0–10 m/s set by the DOT diffraction limit.

Thus, for an upgrade to a 2.5-m mirror the DOT mount can simply stay but a larger canopy is needed for bad-weather telescope protection. A telescope with 4.1 m focal length will just fit within a canopy of 9 m diameter as illustrated in Fig. 5a. This is the size of the canopy for the GREGOR telescope on Tenerife which was installed by us in 2004 and already survived an exceedingly strong storm with gusts of 245 km/hr. More detail is given in Hammerschlag et al. (2006b).

Such size increase also requires an enlargement of the platform including additional support from the ground to make the enlarged platform stiff enough against wind loading. The latter support is shown in Fig. 5a,b. It consists of an isosceles triangle on the north side and four vertical posts – two on the east side and two on the west side. Like the already existing 4 isosceles triangles of the present DOT tower, the additional elements provide a geometry that keeps the platform parallel to the ground at the small but inevitable leg deformation under wind load. More information about geometries for such parallel motion

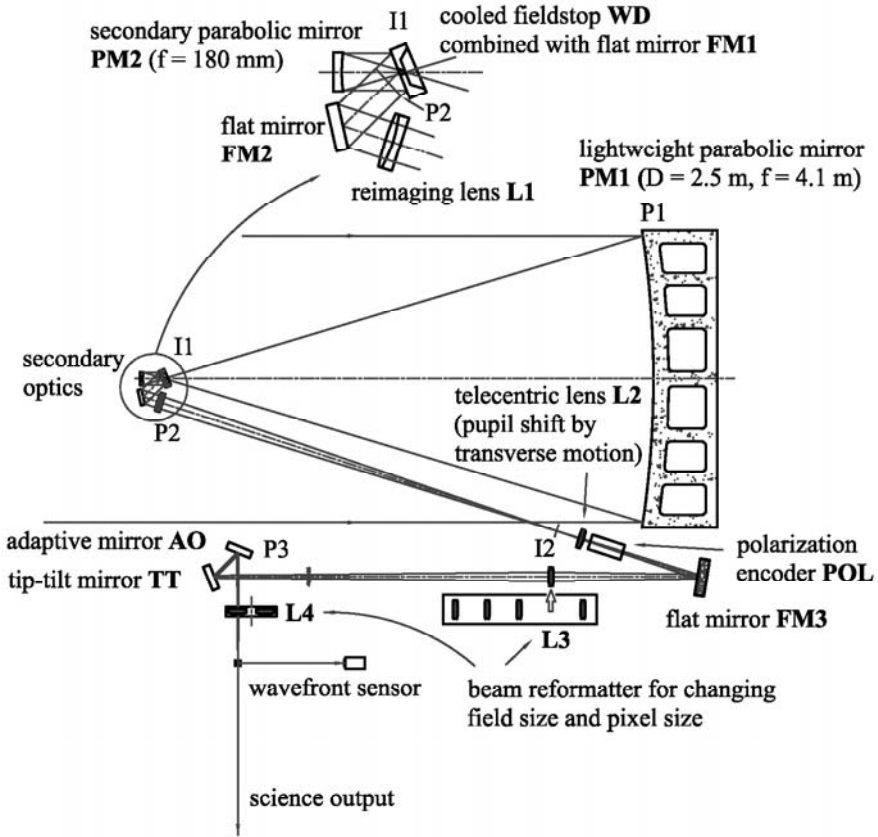


Figure 6. Optical layout for the options II to IV with 2.5-m mirror, similar to the 1.4-m upgrade with the same advantages.

is given by Hammerschlag et al. (2006a). The additional triangle also increases the stiffness against platform rotations around a vertical axis.

The diameter of the additional tubes is set at 406.4 mm, whereas the diameter of the tubes making up the existing tower is 244.5 mm. The choice of a larger diameter over the same free distance of 15 m prevents sensitivity to vortex oscillations (Karman eddies). Consequently, the additional tubes need no rubber dampers as the ones presently mounted between the existing tubes. The additional triangle and two of the four vertical posts require together four additional concrete foundation blocks of $1.5 \times 1.5 \text{ m}^2$ surface. The other two vertical posts rest on the existing foundation blocks.

The optical layout of the Option II setup ($D = 2.5 \text{ m}$, $f = 4.1 \text{ m}$) is shown in Fig. 6 and is similar to Option I ($D = 1.4 \text{ m}$, $f = 2.3 \text{ m}$). Both designs have an opening ratio $f/1.64$. The 2.5 m version has the same important advantages: no coma due to the use of two parabolic mirrors in cascade, low polarization, user-selectable choice between angular resolution and field size, possibility of

transversal pupil shift and accompanying choice of obstruction-free aperture, in this case up to 116 cm.

The existing telescope mount has a central hole through its hour-angle shaft. In the Option II design we propose to let the secondary beam pass through it to a mirror which reflects the beam into a vertical shaft to an optical lab on the ground. In such a transfer system we suggest to use a tandem AO system: the first to correct seeing-imposed wavefront deformations and remaining tip-tilt fluctuations due to the telescope structure, the second for the beam part along the hour-angle axis, through the vertical shaft and in the optical lab. An alternative is to split the AO into a system for instrumentation mounted on the telescope and an independent system for instrumentation in the optical lab.

In the vertical shaft the light should travel parallel over the whole length of the shaft, or large parts of it, in order to eliminate image motion from wind-induced parallel translations between the platform and the ground, which are of the order of 0.1 mm. What remains are small transversal shifts of the optical surfaces following wind gusts and thus slow compared with the seeing motions. Such small pupil shifts do not disturb the AO correction. In order to accommodate a parallel beam over the whole shaft length without use of relay optics, the minimum shaft diameter is $d = \sqrt{2\ell D} \alpha = 330$ mm when a pupil image is located at the middle of the shaft for the following parameter values: transfer length $\ell = 15000$ mm, primary mirror diameter $D = 2500$ mm, field of view $\alpha = 5\pi/(180 \times 60)$ rad = 5 arcmin, and pupil diameter $d/2 = 165$ mm. For a pupil image at one end of the shaft, the diameters of shaft and pupil become $\sqrt{2}$ times larger, 467 and 234 mm respectively. We propose to evacuate the vertical shaft using entrance and exit windows to minimize the internal seeing. The above quantification shows that windows of only 50-cm diameter permit transfer of a diffraction-limited image with 5' field of view without requiring relay optics in the shaft.

There are other optical setups possible that avoid image motion from parallel translation between platform and the ground level. An example is one-to-one image transfer from the top to the bottom with a relay lens halfway up the shaft which shifts over half the value of the platform translation. This can be realized with a passive mechanical construction. The minimum shaft diameter then becomes two times smaller, 165 mm instead of 330 mm. Such a setup may fit better in the overall optics layout.

The relay optics on top of the vertical shaft can and should be connected to the inner platform of the DOT tower in a very stiff way. The inner platform is an important complementary part to the equatorial mount. Fig. 7a shows this inner platform during its assembly at the university workshop in Delft. There are three connection plates for the telescope mount: one on the corner point on the left side, the two others are where the hoist eyebolts are placed on the diagonal from the front to the back in this photograph. This inner platform transforms in an extremely stiff way all forces and moments from the telescope mount to direct forces without moments in its corner points, to which the long downward tower tubes are connected directly.

Another very important mechanical part is the support of the primary mirror. In the open concept, the support has to give stability against the varying wind load on the primary mirror. For the 45-cm primary of the present DOT

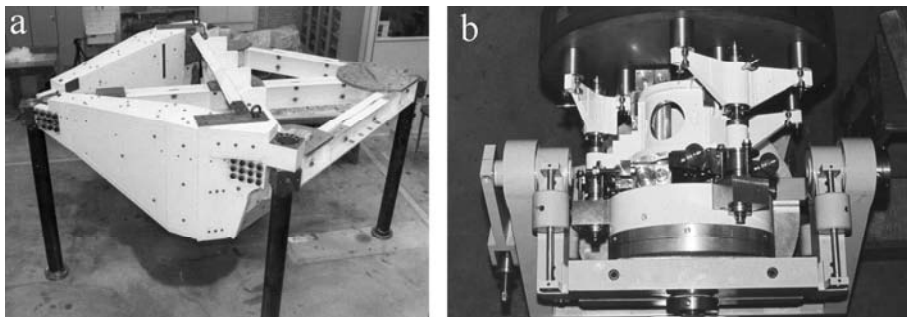


Figure 7. DOT inner platform and mirror support.

(a) The existing inner platform of the DOT is an important complementary part to the equatorial mount and can be re-used together with the mount, also in the broader tower of Options IV & V. This inner platform is shown here during the assembly at the TU workshop in Delft.

(b) DOT mirror with its support in test mount. The 3-dimensional design of the whiffle-trees provides high stability against the varying wind load.

a support system was developed that gives extreme stability using only passive means. A key aspect is the 3-dimensional design of its individual support elements, including the whiffle trees seen in Fig. 7b. This support system is actually much stiffer than was required for the 45-cm mirror. A 2.5-m mirror support can consist of many more support units of similar design. The mirror will be a classical thick mirror, but hollow with a honeycomb structure with triangular cavities for high stiffness. Such honeycomb structures can be realized in common mirror materials like Zerodur, Cervit or ULE, or a new material like Cescic (SiC). The stiff whiffle tree design avoids deformations by variable gravity and wind loads to the extent that the wind pressure is homogeneous over the mirror surface. Only wind inhomogeneities smaller than the mirror diameter, set by shear in the wind field, cause moments that are not carried off by the whiffle trees. These moments are at most a few tens of Nm and are carried by the thick mirror structure. The thickness of the mirror will be larger than the diameter of the AO sub-apertures projected to the primary mirror. Consequently, the deformations by the wind-field shear are small for the AO system due to the high bending stiffness of the thick mirror.

Of course, many variants are possible for the optical layout. The use of focal-plane instrumentation directly on the pointed telescope structure itself remains possible as well. In fact, the existing DOT multi-wavelength imaging system could represent the initial instrument package to start observing as in Fig. 3a, retaining its advantages of absence of image rotation and a relatively simple optical scheme with few components.

4.3. Option III: upgrade to 2.5-m aperture on doubled tower

Option III doubles the DOT tower in height in order to improve the best-seeing occurrence frequency. At La Palma the frequency of excellent seeing observations increases with the telescope height above ground, roughly doubling at double height. This was ascertained in the ATST site selection surveys including La

Palma under the supervision of M. Collados (IAC). Details are given in the final report of the ATST Site Survey Working Group¹. The DOT is situated eleven meters lower than the SST. This is not a disadvantage because the ATST test measurements show that what counts is not the absolute height but the height above the local terrain; the ground-layer turbulence follows its slope. The DOT indeed experiences closely similar seeing to the only slightly higher SST and its SVST predecessor.

The tower height doubling is accomplished in Option III by placing Option II (the existing tower with enlarged platform and additional support carrying a 2.5-m telescope and a GREGOR-copy 9-m canopy) as “upper” tower on top of a new “lower” one. The latter is again an open steel framework with a geometry which maintains parallel platform motion. Fig. 5c,d illustrates this doubling to 30-m height with the telescope in observing and parked position, respectively.

The principle of maintaining parallel platform motion in strong-wind buffeting works as follows. A horizontal wind load on the top platform causes at the “first floor” level between the upper and lower parts a horizontal force of the same strength and in the same direction, plus a moment given by the force multiplied by the height (15 m) of the upper part. The direction of the moment is horizontal and perpendicular to the direction of the wind force. The four original DOT-tower triangles and the fifth triangle added through Option II transfer this horizontal force and moment to the intermediate first-floor level at which a complete network of steel triangles ensures stiffness between the foot points of the five upper-part triangles and four vertical posts.

The proposed lower-part framework between the base at ground level and the first floor consists of five isosceles triangles with exactly the same geometry as in the upper part. In addition, each foot point of the upper-part triangles and vertical posts is connected by a vertical post to the ground level. The diameter of these fourteen posts is the same as for the four in the top part, viz. 406.4 mm. The five lower-part triangles transfer the horizontal load downward from the first floor to the base while keeping these two parallel to each other. The moment caused by the horizontal force on the top platform is transported downward from the first-floor level by the vertical posts attached to the foot points of the triangles of the upper part of the tower. Each moment-component consists of a tensile force and a compressive one of equal value at the two foot points of an isosceles triangle of the top part of the tower. The elongation and shortening of the two vertical posts under the two foot points are equal in value. Consequently, the top point of the isosceles triangle in the upper tower part moves horizontally, maintaining the parallel motion of the top platform.

Elongation and shortening, respectively, of the two lower-part vertical posts under the foot points of an upper-part triangle tilt the latter at the first-floor level. However, such tilts do not influence the top platform because the upper-part triangles have separate endpoints at the first floor. All connections in this

¹ATST Project Documentation Report #0021 Revision A, available at <http://atst.nso.edu/site/reports/> in file RPT-0021.pdf; in particular Appendix “La Palma Height Comparison” in files A13.11.LaPalmaHtComp_Final.pdf and twoheight_r0.pdf. The second file provides additional data to the first one.

floor are horizontal, perpendicular to the vertical posts in the lower part. These connections cannot transport a significant vertical force from one post to another because the bending stiffness is much smaller than the tensile and compressive stiffness.

The vertical component of a wind force on the top platform is transported in a very stiff manner to the first floor by the triangles and posts in the upper tower part. The fourteen posts in the lower tower part transmit these forces directly and hence also in an extremely stiff way to the foundation at ground level.

The horizontal wind forces on the first floor are brought downward by the five isosceles triangles of the lower tower part while keeping the first floor parallel to the ground floor, as explained above.

All together, the top platform remains parallel to the ground under wind loads on the tower. The existing concrete foundation can be maintained while doubling the tower height to 30 m because its 2-m deep concrete blocks are heavy enough to withstand the moments imposed by any storm. In addition, their configuration with the lower-part triangles anchored in separate blocks also favors holding the first floor and top platform parallel to the ground.

The setup with an instrument lab at ground level fed by a vertical vacuum tube remains as in Option II. In the case of parallel-beam image transport, the doubling of the tube length necessitates increase of the pupil and shaft diameters with $\sqrt{2}$, see above. The parallel translations increase from 0.1 mm to about 0.4 mm but this increase can be reduced through larger wall thickness for the lower-part tubes. One-to-one imaging from the top to the bottom can be realized by two relay lenses, midway between platform and the first level and midway between the latter and the ground level, with an intermediate image with field lens located at the first level. This setup offers the possibility of passive mechanical relay lens translation to cancel the image motion at the ground level. The minimum diameter of the shaft then remains 165 mm.

The existing electric elevator can be extended over the full height and then connects the optical lab directly with the platform. The needed space is available in the lower part while the upper part retains the existing open elevator shaft. Further options are closing the cage, or possibly the whole elevator shaft, for easier platform access in bad weather.

Note that a 30-m high tower of concrete cannot meet the stringent demand on absence of platform tilt under large wind loads unless it is much wider than this open-tower design employing tilt cancelation through special geometry. A wide concrete building would present a severe obstacle to the ambient flow and jeopardize the seeing quality at the telescope height. The concrete SST tower is relatively slender (narrower than its platform) and puts the SST imaging element (its 1-m objective) high up in the wind. In this sense even the evacuated SST is an open telescope.

4.4. Option IV: upgrade to 2.5-m aperture with wide 30-m tower

In Option IV the existing equatorial DOT mount and inner platform are to be placed on a new 30-m tower with a larger platform and a folding canopy of 12 m diameter (Fig. 8a) in order to gain working space around the telescope.

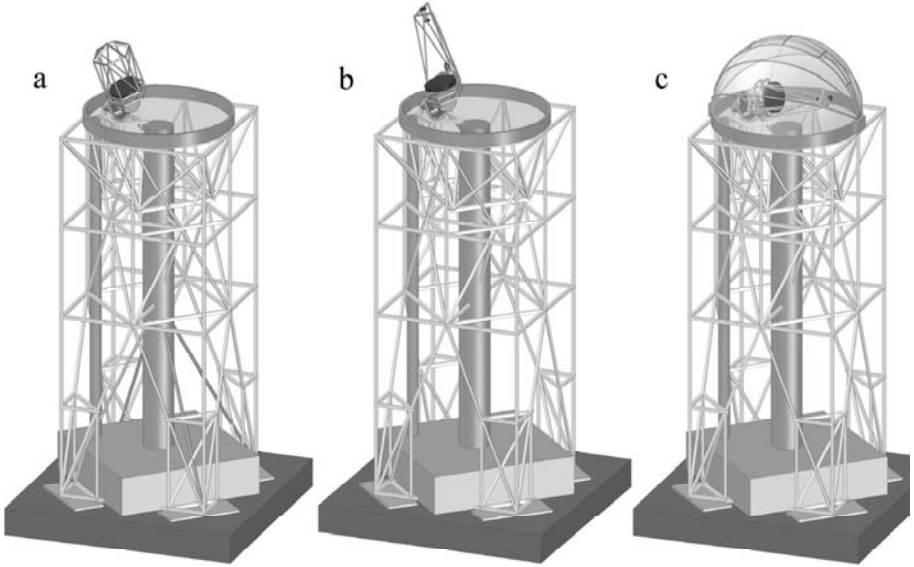


Figure 8. Options IV and V with 2.5-m primary mirror.
 (a) Option IV: new 30-m tower with the 2.5-m telescope of Options II and III. The canopy has a diameter of 12 m. The design for parallel motion of the platform is based on the principle of an outer and inner tower, see text.
 (b) Option V: 2.5-m telescope with off-axis primary mirror on the new tower.
 (c) Option V with closed canopy.

The broader 30-m tower is again designed in a geometry which keeps the top platform parallel to the ground under varying wind loads. This version is based on the principle of having an outer and inner double tower. The outer tower consists of four 30-m vertical posts holding the top platform parallel to the ground. The inner tower consists again of triangle framework providing high translational stiffness as well as stiffness against rotations around a vertical axis. All connections between the inner and outer tower are horizontal and hence perpendicular to the four outer posts so that they do not disturb the parallel motion. The inner telescope platform is connected to the four post tops with a separate framework hanging free of the inner tower. A more detailed description of this tower design is given in Hammerschlag et al. (2006a). Its characteristics were checked through simulations with finite-element analysis (program ANSYS, Lanford et al. 2006).

The post-focus beam travels down through an evacuated shaft to an optical lab on the ground, similar to the Option-III design. In the center of the tower an elevator shaft can be placed as indeed added in Fig. 8. The 12-m canopy would be a further development of the 9-m GREGOR canopy. The tower can be placed on a foundation of 4 blocks of concrete, each with a surface of 3×5 m.

The tower shown in Fig. 8a–c implements the concept for a 30-m tower. The design principle of an outer tower to hold the platform parallel and an

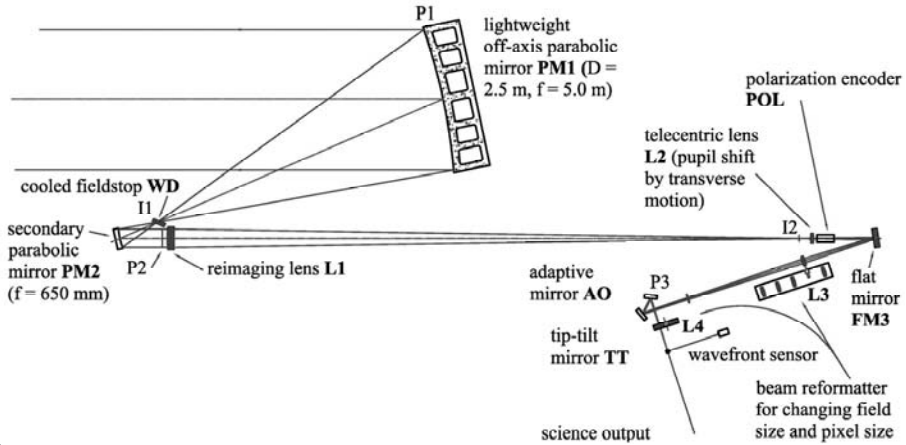


Figure 9. Optical layout of Option V with 2.5-m off-axis primary mirror.

inner tower for stiffness remains suitable for yet higher towers: the shown four-level geometry is suitable for heights up to 60 m, while larger height requires more stories.

4.5. Option V: upgrade to 2.5-m off-axis aperture on 30-m tower

In this final and most expensive option an off-axis parabolic primary mirror is purchased to obtain a fully clear aperture. Figure 8b,c shows such a telescope placed on the new 30-m tower of Option IV, in observing position and in parked position with the folding canopy closed. Figure 9 shows the optical layout. The focal length of the primary mirror is 5 m. The distance between the optical axis and the nearest rim of the primary mirror is one third of its diameter, hence 0.833 m. A user-selectable choice between angular resolution and field size and the possibility of transversal pupil shift are again incorporated with a system similar to that in the on-axis design. For the off-axis design the transversal pupil shift provides the option to use a smaller pupil close to the optical axis to reduce partial polarization.

The choice between on-axis and off-axis design has many aspects and tends to invite many different opinions. Mechanically, both are possible. Figure 10a,b shows in more detail how also in an off-axis setup the mechanical structure of the telescope top can be designed to guarantee stiff support of the secondary mirror. Optically, the off-axis design requires extremely precise alignment between the primary and the secondary mirrors transverse to the optical axis because otherwise the coma correction becomes incomplete.

5. Cost Estimates

Table 1 gives our cost estimates of the various upgrade options. These do not include the purchase of the primary mirror, nor the cost of post-focus instrumentation, nor the effort and running costs of the DOT team.

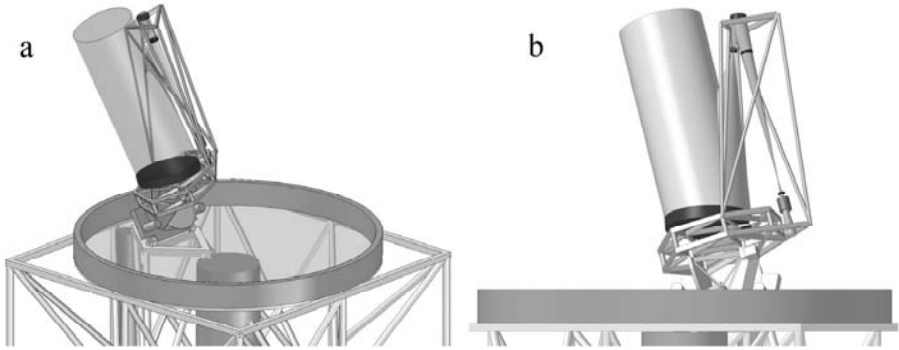


Figure 10. Off-axis design with stiff geometry of the framework supporting the secondary mirror in the telescope top.

(a) View from above.

(b) View from behind, showing the framework geometry more clearly. The optical beams are drawn as cylinders and cones. The beam from the primary mirror to the primary focus passes under the diagonal tube in the framework.

The price of a primary mirror depends on market constraints such as the order book and capacity of the few firms capable of fabrication of large optics, for example the availability of a blank, the occupancy of large polishing machines, etc. We note that although SiC is the preferential mirror material for large solar telescopes particularly because of its excellent thermal conductivity (60 times higher than Zerodur), the fully open designs proposed here can live with Zerodur because their mirror flushing becomes sufficiently effective already at medium wind speeds. The larger weight of Zerodur poses no problem in these designs because the DOT mount, re-used in all of them, is sufficiently over-dimensioned (see above).

The cost of post-focus instrumentation obviously ranges from low (re-usage of the existing DOT multi-camera multi-wavelength imaging system) to large (the image lab at ground level harboring many instruments). We envisage emphasis on high-cadence line-profile sampling with LC polarimetry for large fields of view and two-dimensional multi-line spectrometry including spectropolarimetry with phase-diverse MOMFBD restoration using a fiber field-of-view reformatter from two-dimensional to slit geometry (cf. Rutten 1999).

The DOT team is indispensable in the proposed upgrades not only because the latter use bits and pieces of the present DOT but yet more because of the team's expertise in tower and telescope open-design principles, computational verification of these, hardware solutions, and the La Palma environment. In addition, the teams would supply the intensive contacts with the university workshops (at Utrecht and Delft) whose contributions are budgeted separately in the next-to-last column in Table 1. A rough estimate of the DOT-team manpower, management, and operational costs to undertake the proposed upgrades ranges from 250 kEuro/year (the present DOT operations budget) to 500 kEuro/year.

The costs listed in Table 1 under "Optics" cover the prime-focus and subsequent packages. "Telescope structure" includes a new mirror support. The University workshops are needed for design work on the telescope structure,

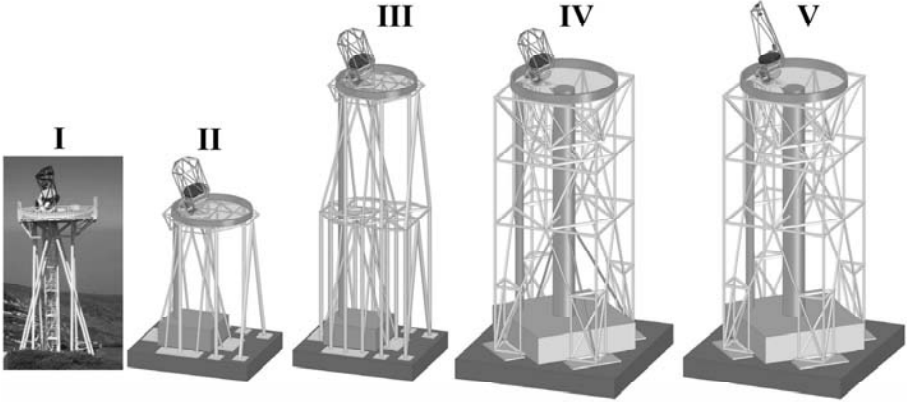


Figure 11. Overview of the five options. I: upgrade of the present DOT to 1.4-m aperture. II–IV: 2.5 m aperture with increasing tower height and platform width. V: 2.5 m off-axis version.

Table 1. Cost estimates in kEuro, excluding the primary mirror, post-focus instrumentation, and DOT-team effort.

Option*	Optics	Telescope structure	Tower+ platform	Canopy	University workshops	Total
I	200	300			300	800
II	300	400	300	600	300	1900
III	400	400	900	600	600	2900
IV	400	400	3200	1100	600	5700
V	600	400	3200	1100	600	5900

- * I 1.4-m aperture with existing 7-m canopy and existing 15-m tower
 II 2.5-m aperture with 9-m GREGOR-like canopy and widened 15-m tower
 III 2.5-m aperture as Option II with a doubled 30-m tower
 IV 2.5-m aperture with 12-m canopy and new, wide 30-m tower
 V the same as Option IV with a 2.5-m off-axis primary mirror

tower and platform, in addition to the industrial manufacturing costs listed in the respective columns. Special small parts and test equipment must also be produced in these workshops. The increase in workshop costs from Option II to Option III reflects additional design work for the higher towers, in particular the far-from-trivial joints in the corner points, the beam transfer tube, and the elevator. The joints need very careful designing in order to maintain the high stiffness of the overall geometry, and will need complex special parts that are best manufactured in-house.

Figure 11 shows a pictorial overview of the five options. In summary: without inclusion of the DOT team, the primary mirror, and post-focus instrumenta-

tion, Option I takes roughly 1 MEuro, Option II 2 MEuro, Option III 3 MEuro, and options IV and V 6 MEuro. The latter two options are costlier due to their new tower and foundation.

These various options may be realized in overlapping phases with continued observing. For instance, the Option-II platform and canopy enlargements can be realized keeping the DOT in operation, with fast subsequent upgrading of the telescope. The Option-III tower doubling may follow on the Option II aperture upgrade. In Options III-V the higher tower may be realized first and tested with the existing telescope before the latter is replaced. Other variants and option combinations are also possible.

6. Conclusion

The DOT telescope and tower combine rigorously open design with extraordinary stiff construction. This combination was achieved through the application of special geometries and the careful attention to the design of joints and drives that is necessary to indeed realize the geometrical stiffness. The excellent DOT high-resolution observations have amply proven both the open concept and the DOT's pointing stability.

We would like to enlarge the DOT and profit fully from its concept. Only relatively moderate investments are needed through re-using existing DOT parts, in particular the equatorial mount and drives which are indeed oversized for the present 45-cm primary mirror. In this paper we have outlined strawman designs for upgrades to 1.4-m and 2.5-m aperture, optionally adding a groundbased post-focus lab and 30-m tower height to double the frequency of super-seeing. Even with a 2.5-m primary mirror diffraction-limited pointing stability can be reached without compromising the rigorously open construction of both the telescope and the tower.

We welcome partners to share in DOT operation and the realization of one of these upgrades.

Acknowledgments. We thank the CSPM organisers for a very good meeting. The DOT is presently operated by Utrecht University at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias with funding from Utrecht University and the Netherlands Graduate School for Astronomy NOVA. A. P. L. Jägers is supported by the Netherlands Technology Foundation STW. R. J. Rutten acknowledges travel support from the Leids Kerkhoven-Bosscha Fonds and the European Solar Magnetism Network.

References

- Bettonvil F. C. M., Hammerschlag R. H., Sütterlin P., Rutten R. J., Jägers A. P., Snik F., 2004, in J. Oschmann (ed.), *Astronomical Telescopes and Instrumentation*, Procs. SPIE 5489, 362
- Bettonvil F. C. M., Hammerschlag R. H., Sütterlin P., Rutten R. J., Jägers A. P. L., Slieden G., 2006, in I. S. McLean, M. Iye (eds.), *Ground-based and Airborne Instrumentation for Astronomy*, Procs. SPIE 6269, paper 62690E
- Hammerschlag R. H., 1981, in R. B. Dunn (ed.), *Solar Instrumentation: What's Next?*, Proc. Sacramento Peak Nat'l Obs. Conf., Sunspot, New Mexico, 547
- Hammerschlag R. H., 1983, Procs. SPIE 444, 138

- Hammerschlag R. H., Bettonvil F. C. M., Jägers A. P. L., 2006a, in E. Atad-Ettdgui, J. Antebi, D. Lemke (eds.), *Optomechanical Technologies for Astronomy*, Procs. SPIE 6273, paper 62731O
- Hammerschlag R. H., Bettonvil F. C. M., Jägers A. P. L., Sliepen G., Snik F., 2006b, in *Spatial Structures*, Procs. IASS, paper 108
- Keller C. U., von der Lühe O., 1992, *A&A* 261, 321
- Lanford E., Swain M., Meyers C., Muramatsu T., Nielson G., Olson V., Ronsse S., Vinding Nyden E., Hammerschlag R., Little P., 2006, in Monnier, John D., Schöller, Markus, Danchi, William C. (eds.), *Advances in Stellar Interferometry*, Procs. SPIE 6268, paper 626814
- Rutten R. J., 1999, in T. R. Rimmele, K. S. Balasubramaniam, R. R. Radick (eds.), *High Resolution Solar Physics: Theory, Observations, and Techniques*, Procs. 19th NSO/Sacramento Peak Summer Workshop, ASP Conf. Ser. , Vol. 183, 296
- Rutten R. J., Bettonvil F. C. M., Hammerschlag R. H., Jägers A. P. L., Leenaarts J., Snik F., Sütterlin P., Tziotziou K., de Wijn A. G., 2004a, in A. V. Stepanov, E. E. Benevolenskaya, A. G. Kosovichev (eds.), *Multi-Wavelength Investigations of Solar Activity*, Procs. IAU Symposium 223, Cambridge University Press, 597
- Rutten R. J., Hammerschlag R. H., Bettonvil F. C. M., Sütterlin P., de Wijn A. G., 2004b, *A&A* 413, 1183
- Snik F., Bettonvil F. C. M., Jägers A. P. L., Hammerschlag R. H., Rutten R. J., Keller C. U., 2007, in B. W. Lites, R. Casini (eds.), *Procs. 4th Solar Polarization Workshop*, ASP Conf. Ser. , in press
- van Noort M., Rouppe van der Voort L., Löfdahl M. G., 2005, *Solar Phys.* 228, 191
- van Noort M. J., Rouppe van der Voort L. H. M., 2006, *ApJ* 648, L67