

DOT++: The Dutch Open Telescope with 1.4-m aperture

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ABSTRACT

The Dutch Open Telescope (DOT; <http://dot.astro.uu.nl>) on La Palma is a revolutionary open solar telescope, on an excellent site, on top of a transparent steel tower, and uses natural air flow to minimize local seeing. The aim is long-duration high-resolution imaging with a multi-wavelength camera system. In order to achieve this, the DOT is equipped with a diffraction limited imaging system and uses the speckle reconstruction technique for removing the remaining atmospheric turbulence. The DOT optical system is simple and consists currently of a 0.45m/F4.44 parabolic mirror and a 10x enlargement lens system.

We present our plans to increase the aperture of the DOT from 0.45m to 1.4m. The mirror support and telescope top shall be redesigned, but telescope, tower, multi-wavelength camera system and speckle system remain intact. The new optical design permits user selectable choice between angular resolution and field size, as well as transversal pupil shift introducing the possibility to use obstruction free apertures up to 65cm. The design will include a low order AO system, which improves the speckle S/N substantially during moderate seeing conditions.

Keywords: diffraction limited imaging, solar telescopes, telescope optics, telescope construction, speckle masking, adaptive optics, seeing, wind, silicon-carbide.

1. INTRODUCTION

The Dutch Open Telescope (DOT, Figure 2) is located at the Roque de los Muchachos Observatory on La Palma¹⁻⁵. The laminar wind flows make La Palma a world-class site. Both the telescope and tower are open, i.e. transparent for the wind. It consists of a 15m-high open framework tower and a telescope without a dome during observations. Already when there is a light breeze it limits the solar heated boundary layer of turbulent convection to heights below the telescope and flushes the telescopes itself, mixing the air and making the air temperature homogeneous. No warm air bubbles are forced upwards against solid walls and no heat is produced by the tower itself.

The open concept was revolutionary. So far, high-resolution solar telescopes used evacuation to avoid internal turbulence.

The DOT purely uses the speckle reconstruction technique for removing atmospheric turbulence⁶. The resulting DOT movies are world famous (see the DOT-website <http://dot.astro.uu.nl>). Figure 1 shows an example. Of particular importance is the fully restored field and the excellent temporal sequence homogeneity. When the La Palma seeing is good enough for speckle reconstruction, which occurs fairly frequently, an entire multi-hour image sequence consistently possesses diffraction-limited resolution.

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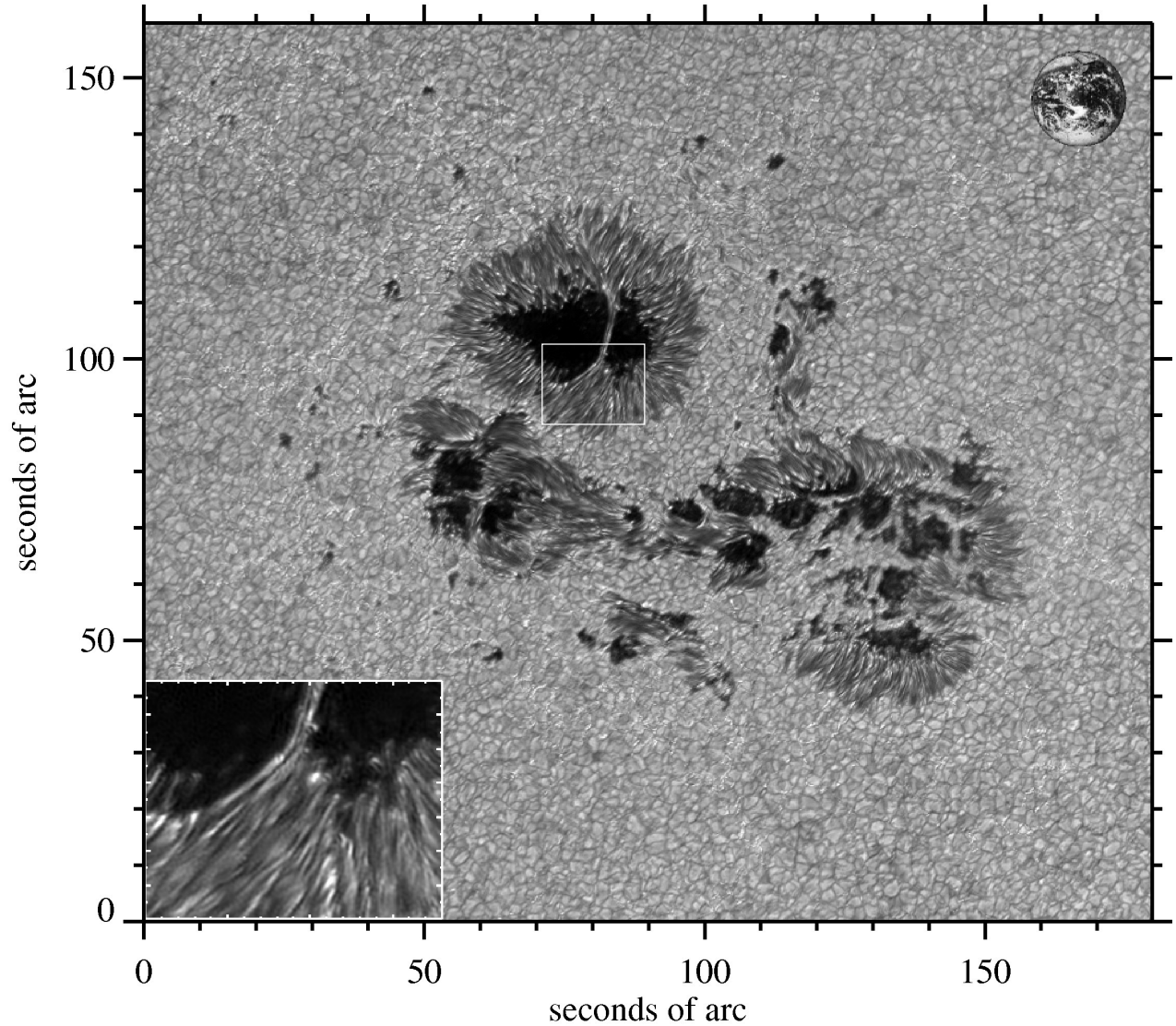
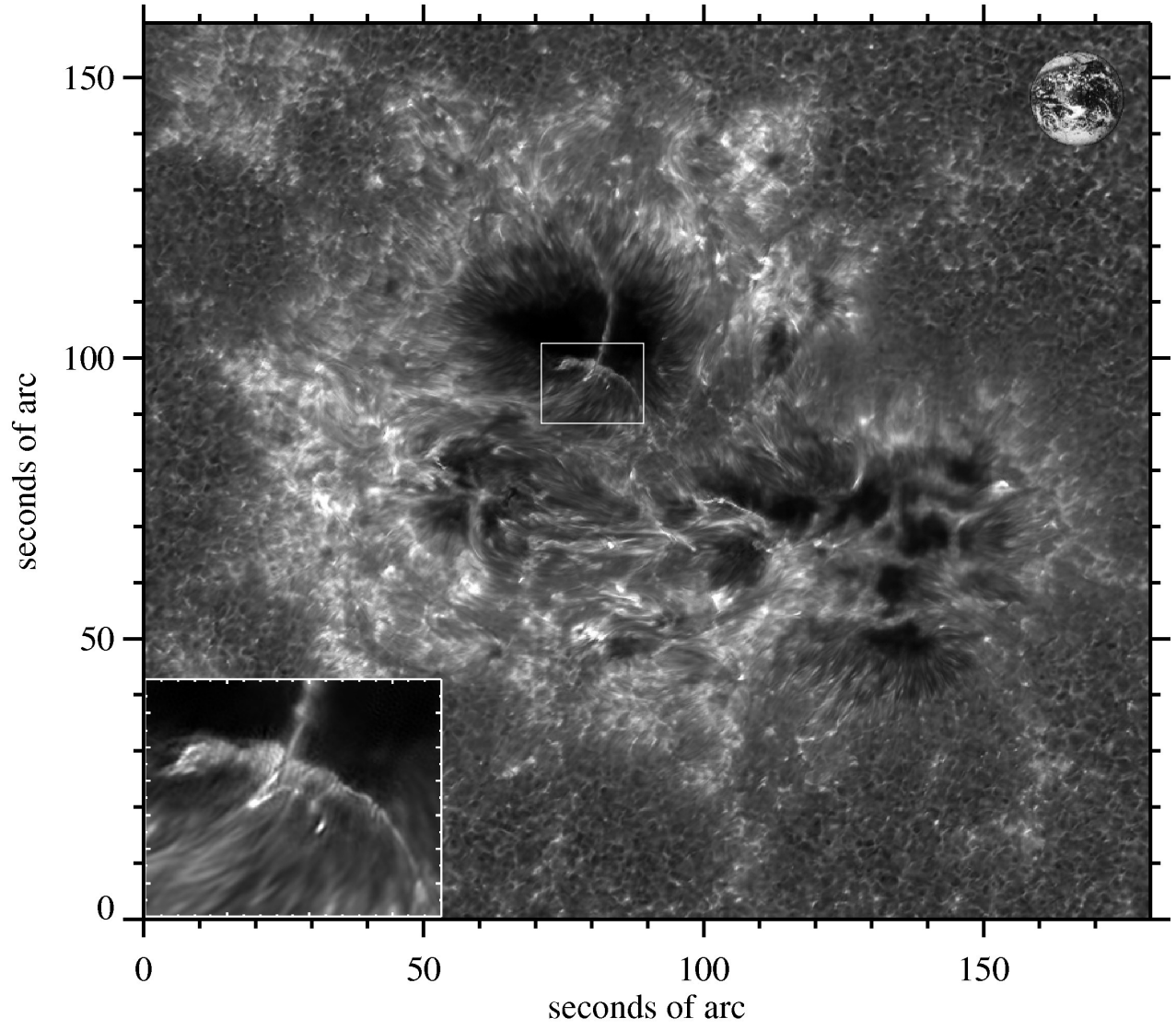


Fig. 1: Example of synchronous DOT imaging in two wavelength channels: Sunspot AR10375 on June 06, 2003. *This page:* 4-frame mosaic in the Fraunhofer G-band (430.5nm); *next page:* 4-frame mosaic in Ca II H (396.8nm). The G-band samples the deep photosphere and shows convective cells (granules); Ca II H samples the lower chromosphere a few hundred kilometers higher and shows magnetic structures above the photosphere. In the upper right the earth is shown for comparison. The cutout shows a detail of the penumbra with a remarkable 'bridge' which is only visible in the Calcium image. The tick marks in the cutout are 1". The smallest details visible have a resolution of 0.2", corresponding to 140km. For more DOT images and movies see the DOT-website <http://dot.astro.uu.nl>.



In 2004 the DOT opened to the solar physics community¹. By 2005 the DOT will fill a major solar physics niche as the premier 0.2'' tomographic mapper of the solar atmosphere, frequently sharing in international multi-telescope campaigns combining many different diagnostics (Stokes vector polarimetry, Doppler mapping, EUV imaging)^{1,7}. High-resolution large-field high-cadence long-duration observation is a must, as solar physics becomes a science of movies, preferable even with spatial resolutions far below 0.1''^{8,9}.

The DOT has modest size. But its successful demonstration of the open principle and its ability to be upscaled towards much larger apertures (no need for lenses or windows to close the vacuum tank), together with the rapid development of adaptive optics in solar imaging, started a new phase in solar telescope engineering^{10,11}.



Fig. 2: a) The Dutch Open Telescope (DOT) on the La Palma, observing the sun; b) close up of the telescope; c) detail of the 45 cm primary mirror.

2. PRESENT CONFIGURATION

The tower and telescope are extraordinarily stiff to avoid image shake from wind buffeting and are at the same time transparent. The tower consists of parallel triangles minimizing rotations rather than translations. Details are given in^{2,4}. The telescope is of the equatorial fork type, very compact and rigidly built, with the primary mirror not below but above the declination axis. In this way, around noon the complete optical light path is above the telescope, free in the air and maximizing the natural air flushing effect. The mount contains a novel drive system combining high stiffness with minimal friction and stick-slip^{2,3,4,12}.

The present optical system (Figure 3) consists of a 450mm F/4.44 parabolic mirror and a 10x enlargement lens system directly after the primary focus and still inside the primary beam. In the primary focus a reflective and watercooled field-stop is located³. On axis an image plane is formed where a CCD-camera is placed (Fraunhofer G-band, 430.5nm). On the side of the telescope top a multi-wavelength imaging system is situated, providing light to 5 additional wavelength channels, Ca II H (396.8nm), H-alpha (656.3nm), Ba-II (455.4nm), and two continuum channels (432 and 651nm)^{1,3,13}. This multi-wavelength system is fed by a beamsplitter just behind the enlargement lens. The channels are realized with use of dichroic splitters and all cameras work simultaneously and synchronously. The complete optical system is precisely aligned and diffraction limited. A detailed description of the whole system can be found in³.

All channels use Hitachi KP-F100 cameras (1296x1030 pixels, $6.7\mu\text{m}^2$, 12 frames/sec.) which transmit their images to an acquisition computer, recently upgraded with new hard disks having in total 1.8 Terabyte of storage capacity, sufficient for 8-hour runs with all 6 cameras.

This summer the DOT Speckle Processor (DSP) becomes operational, a cluster consisting of 70 processors (2.4 GHz Intel Xeons) to reconstruct all data within 24 hours. The cluster is water-cooled and the heat is stored in a watertank from which it is only released during sunset en sunrise, avoiding disturbance of observations.

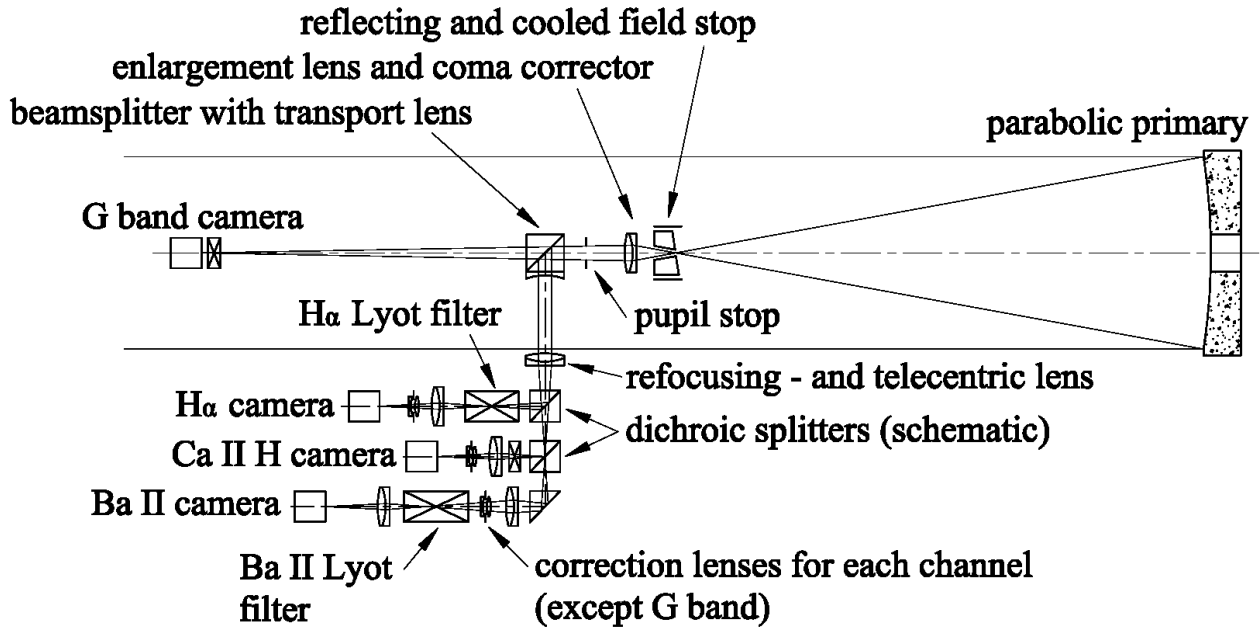


Fig. 3: Optics sketch of the present DOT optical layout with 0.45m parabolic primary mirror. For clarity the multi-wavelength system (below the primary beam) is simplified and the two continuum channels have been neglected. In reality the dichroic splitters are not cubes but mirrors reflecting on a small angle.

3. FROM 0.45-M DOT TO A 1.4-M DOT++

We plan to replace the present 45cm primary mirror with a 140cm mirror. This 3-fold increase in aperture decreases the diffraction limit to $0.07''$ at 430nm. The proposed tripling will maintain the DOT's science value as tomographic context imager, fully complementary to adaptive-optics spectropolarimetry.

The telescope mount is large enough to accommodate a larger mirror, see Figure 2c which illustrates the modest size of the current mirror relative to the telescope construction. A 140cm mirror is the maximum which fits in the telescope, without the need for big and expensive reconstructions. The telescope mount is strong enough and can support the increased weight. The current multi-channel imaging system will remain and gets a place on the up-scaled DOT.

Figure 4 schematically shows the new optical layout. In the upper left corner the multi-wavelength system is shown in a simplified way. The system is designed for an F-ratio of F/45 (the physical pupil stop with a diameter of 15.45mm is 696mm located from the image plane). The present 10x enlargement lens (Figure 3) will be removed, and the whole camera system, including the now on-axis G-band camera, will get a place outside the primary beam.

The primary mirror PM1 is parabolic and has a focal length of 2.3m. This is the maximum dimension which fits within the retractable tent enclosure which protects the telescope in severe weather conditions. The secondary mirror PM2 is parabolic too and has a focal length of 100mm and a diameter of 70mm. The heat load on PM2 is 5 times more than the heat load on the primary mirror. Experience with the DOT enlargement lens and laboratory measurements showed that this is a safe criteria³.

Mirror PM2 forms an image at infinity. Two parabolic mirrors in cascade have no coma; consequently the whole field is diffraction limited. The alignment of the mirrors is about 20 times more critical compared to the present DOT optics, but realistic when similar alignment techniques are used as applied at the DOT³.

In the primary focus, in between the mirrors PM1 and PM2, a diaphragm WD is located, which is on the rear side combined with a flat mirror FM1. The diaphragm furnishes the field stop and has a diameter of 2mm (3 arcminutes when measured on the sky). The field stop is water-cooled and has air suction around it. Mirror FM1 intercepts the light beam coming from mirror PM2 and reflects the beam towards flat mirror FM2, which directs the beam backwards to a small mirror FM3, located next to the primary mirror PM1.

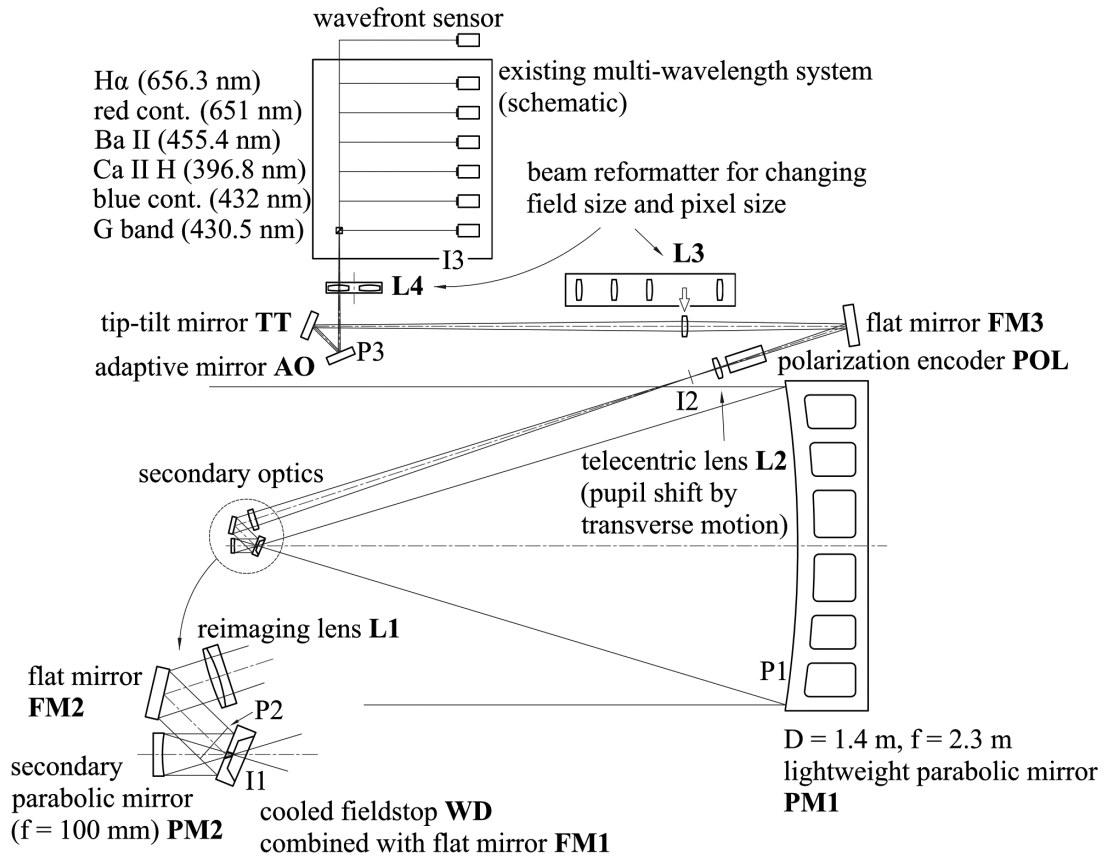


Fig. 4: Optics scheme for the DOT++. Sunlight enters the telescope from the left. The box at the upper left represents the current multi-wavelength imaging system which remains the same. PM1 is the parabolic primary; PM2 the parabolic secondary; L1, L2, L3, L4 are imaging- and field lenses. P1, P2, P2 are pupil planes; I1, I2, I3 image planes. For an explanation see text.

From this point there are multiple ways to direct the light beam towards the multi-wavelength system. We suggest a system based on lenses as illustrated in Figure 4. With lenses it is easy to adapt the optical layout to the multi-wavelength system and to realize a telecentric light path for accommodation of a polarization encoder POL.

The first lens L1 is located directly after flat mirror FM2. This lens generates an intermediate image I2 just before the polarization encoder POL. L1 will be a triplet with good color correction¹⁴. Close to this intermediate image I2 a field lens L2 images the pupil into infinity, creating the telecentric light path. After this lens the polarization encoder POL can be placed.

Lens L3 is in between the polarization encoder POL and the -in the multi-wavelength system located- pupil P3. At P3 the physical pupil stop of 15.45mm is located. L3 images the pupil from infinity back onto P3. Lens L4 which is near pupil P3 is finally responsible to put the image plane I3 on the right location in the multi-wavelength system.

The effective focal length of the telescope will be 63m. The optical setup includes an AO system which will be described later.

With the described optical design it is possible to change the size of the entrance aperture. Consequently the telescope size can be adapted to the seeing conditions. At days with non-optimal seeing it is of advantage to increase the pixel- and field size. Large fields are attractive too when catching flares and prominence eruptions. When the seeing turns excellent, one can rapidly tune to high resolution.

To realize this, there is a whole ensemble of lenses L3 which can be interchanged. Only one lens L3 is placed into the beam. The lenses have different focal lengths and must be shifted into the light beam on different locations in order to fulfill the condition of imaging the pupil from infinity onto P3. Due to the different focal lengths the size of the entrance pupil at P3 is different, or the other way around, because of the size of the physical pupil stop at P3, a lens L3 with a longer focal length projects a smaller pupil stop backwards on the primary mirror PM1, resulting in a smaller entrance pupil P1.

Because the change to a lens L3 with another focal length influences the position of the image plane as well, another lens L4 is necessary too. These lenses L4 can be housed in a rotating revolver. By changing to another aperture, thus choosing another combination of L3 and L4, the pixel-size as measured on the sky automatically scales with the diffraction limit belonging to the chosen aperture. As a consequence the field of view increases when a smaller aperture is chosen.

Lens L2 shall be mounted on a transverse X/Y-stage and can be shifted perpendicular to the optical axis. A shift of L2 generates a movement of the field stop P3 projection on the primary mirror PM1. For the smaller aperture this means that the pupil can be shifted such that the primary beam is completely unobstructed. An unobstructed light path is possible with apertures up to 65cm (Figure 5).

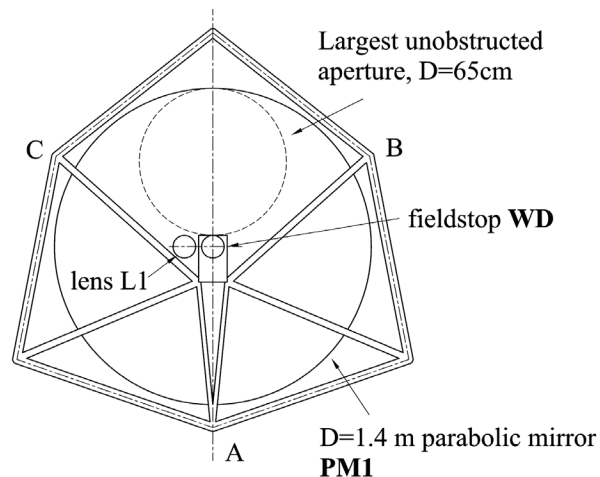


Fig. 5: Front-view of the DOT++. For up to apertures of 65cm the DOT++ is obstruction-free.

Instead of a layout using lenses an optical layout which is only based on mirrors is possible too. Instead of flat mirror FM3 a spherical mirror is placed which reflects the light coming from FM2 towards a second spherical mirror which is located next to FM2. This mirror sends the light beam back to a flat mirror located next to the first spherical mirror. This mirror sends the light towards the multi-wavelength system where it arrives with the correct pupil image at P3 and the correct location of the image plane. By changing the focal length of the spherical mirrors the effective F-ratio of the telescope can be changed. Disadvantage of the setup is that the optical path length is doubled and therefore more sensitivity to seeing.

The present DOT camera field measures 116'' over the diagonal, as determined by the effective focal length (19.75m) and CCD dimensions (1296x1030 pixels, 6.7 μ m square). The maximum field for the DOT and multi-wavelength system is 3 arcminutes and therefore 2k x 1.6k cameras are permitted. For the DOT++, the field can vary from 3' (at 0.45m aperture) to 1' at full resolution. The optical layout of DOT++ permits larger fields, but then the multi-wavelength system needs to be redesigned. The Lyot-filters set the upper limit.

In the present optical system of the DOT, the enlargement lens (Figure 3) corrects for coma as well but introduces sphero-chromatism due to the high F-ratio. This is corrected within each camera channel separately by use of weak correction lenses. With the described DOT++ system based on two parabolic mirrors these correction lenses can be left out. After mirror PM2 only lenses with small F-ratios are used, with neglectable sphero-chromatism. Without the correction lenses of the present DOT it becomes rather easy to change the image scale on the CCD with the DOT++.

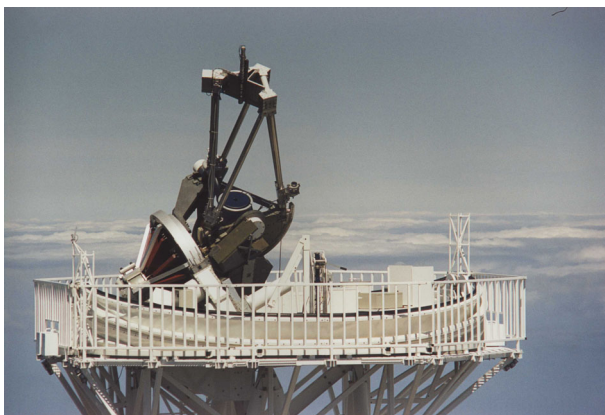
4. MECHANICAL CONSIDERATIONS

The primary mirror will be lightweight and hollow. Main design consideration is to make the mirror stiff in itself; it will get a diameter/thickness ratio of 5 or even less. The mirror is manufactured from Zerodur, Cervit, ULE or Silicon-carbide, where the final choice will be affected by the experience with Silicon-carbide as mirror material in other projects¹⁰. Silicon-carbide is well known because of its good thermal conductivity but its linear thermal expansion coefficient is worse compared to the other materials. Zerodur, Cervit and ULE are good and safe alternatives because of their insensitivity in optical performance to temperature changes. Because of the inherent rigidity, the mirror support can be constructed considerably easier than the present DOT mirror mount.

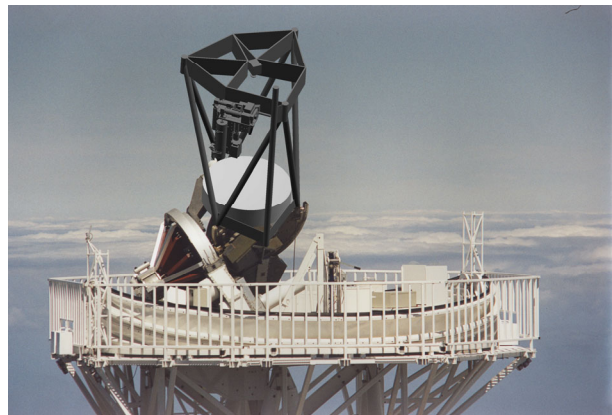
The field stop WD will be combined with the flat mirror FM1 because of space limitations. Care has to be taken not to introduce deformations in FM1 caused by the heat load on the field stop, especially because the pupil plane P2 is nearby FM1. As the case with the present DOT field stop, minimizing seeing effects will be done by the combination of reflection, absorption, and air suction. The heat-load for DOT++ is about 10 times higher than for the original DOT, and this will be handled by improved reflectance of the surface, a higher water flow rate, and decreased thermal resistance. In particular the channel-width in the heat-sink determines largely the thermal resistance, both in terms of effective cooling surface and the heat transfer coefficient¹⁵. The combined WD+FM1 unit will be manufactured from Silicon-carbide. Silicon-carbide as mirror material has a big advantage here because of the high thermal conductivity. It can be sintered, making efficient porous heat-sinks realizable. The manufacturing of small optical components (the field stop has a diameter of 10cm) with a complex shape and a high optical quality is feasible nowadays. The manufacturing of prototypes is foreseen.

The telescope top structure, being the open framework construction above the declination axis needs to be changed to accommodate the new optical setup. Tower, drives, bearings and mount remain however identical. Figure 6 gives an impression of what the DOT ++ will look like.

The major design requirement is stiffness against vibration by wind. Bending and slow thermal effects is removed by active movement of PM2. The field stop and flat mirror WD+FM1, the parabolic secondary PM2 and flat mirror FM2, all located in the top and supported by plate shaped 'spiders' with their top towards the light beam with on top slightly broader baffle strips which avoid stray light caused by grazing sun light. The total central obstruction is smaller than the present configuration, which is 10 %.



A



B

Fig. 6: Comparison between the telescope top of the present DOT (A) and the new top of DOT++ (B).

5. IMAGE RECONSTRUCTION

The success of speckle reconstruction on the sun decreases with increasing aperture. To reach complete restoration with a larger aperture better seeing is required.

First we studied the seeing quality from DOT data. The conclusion is that on La Palma 10cm seeing occurs rather frequently. On average two-weeks campaigns hit 10cm seeing at least some days in the season from mid-May until mid-October and superb seeing occurs at any time, also in winter. Figure 7 shows details about the seeing quality as obtained from DOT data from 1999 until 2002. Figure 8 illustrates that good day-time seeing may last all day.

Secondly, we used a computer simulation for a quantitative estimation of the feasibility of speckle reconstruction with 140cm apertures with help from C.U. Keller (NSO Tucson) who investigated similar issues in the ATST design. The results of this simulation and details are given in Figure 9. We conclude that solar speckle reconstruction is possible with a 140cm telescope already for Fried parameters $r_0 = 10$ cm. The results of the simulation show respectively, that with 140cm aperture and 10cm seeing speckle reconstruction delivers a much better result than frame selection, and that low-order adaptive optics (AO) enhances speckle reconstruction to nearly diffraction-limited imaging.

In general, AO wavefront correction, phase-diverse image restoration and speckle reconstruction are complementary techniques but combination is desirable and is now being implemented at different telescopes. The post-processing phase-diverse and speckle techniques usually serve to increase the field over the central iso-planatic field corrected by the high-order AO. The present DOT reaches nearly diffraction limited resolution with Fried parameters of already 7cm over its whole field with speckle reconstruction alone. DOT++ will like the present DOT also be used especially for producing large field image sequences and will apply AO-improved speckle reconstruction.

In the optical layout (Figure 4) the AO system is included and located close to pupil P3. The wavefront sensing camera will be added as an additional channel in the multi-wavelength system. Low order AO system with 20-40 degrees of freedom are widely available now and require minimal system development. Keller's cheap system on the McMath-Pierce telescope is an illustrative example¹⁶.

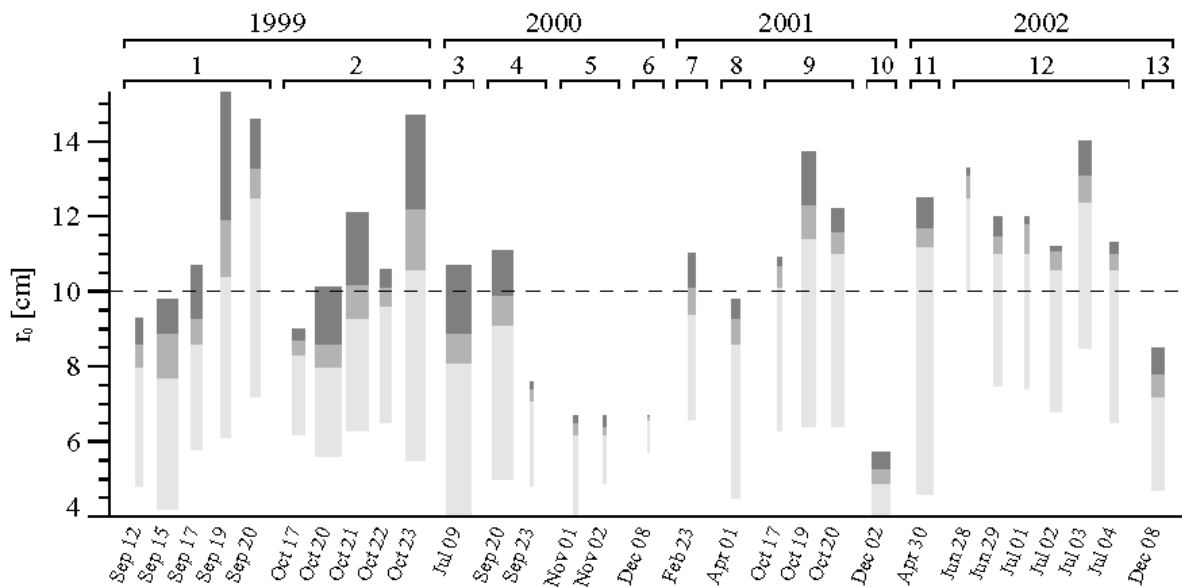


Fig. 7: Seeing during thirteen DOT observing campaigns in the period 1999-2002. Each bar represents a fully processed speckle sequence providing quantitative r_0 estimates per speckle burst. The bar tops specify r_0 for the best burst, the contrast changes to intermediate grey show the mean value for the best 10% bursts, the next contrast changes the mean of the best 30%. The bar bottoms show the worst value, but this is not significant as runs are generally continued into bad seeing. The bar widths show the sequence durations; the longest (October 20, 1999) lasted 200 min. Although many campaigns were outside the best-seeing season, good sequences were obtained in nearly all campaigns. Restriction to $r_0 > 10$ cm during 1/3 of the time passes 1/3 of these sequences, with a good change of getting at least one per campaign.

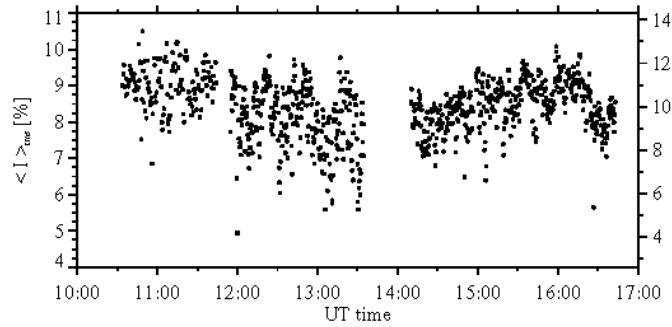


Fig. 8: Example of diurnal seeing variation on La Palma with the DOT on September 20, 1999, showing that good seeing can last all day. Three runs were taken, the first in speckle burst mode, the other two in frame selection mode. The first run, which lasted until 11h45 UT was speckle reconstructed providing the Fried parameter r_0 . For the frame selection runs the contrast of the solar granulation was measured and converted into a Fried parameter using the first run as calibration.

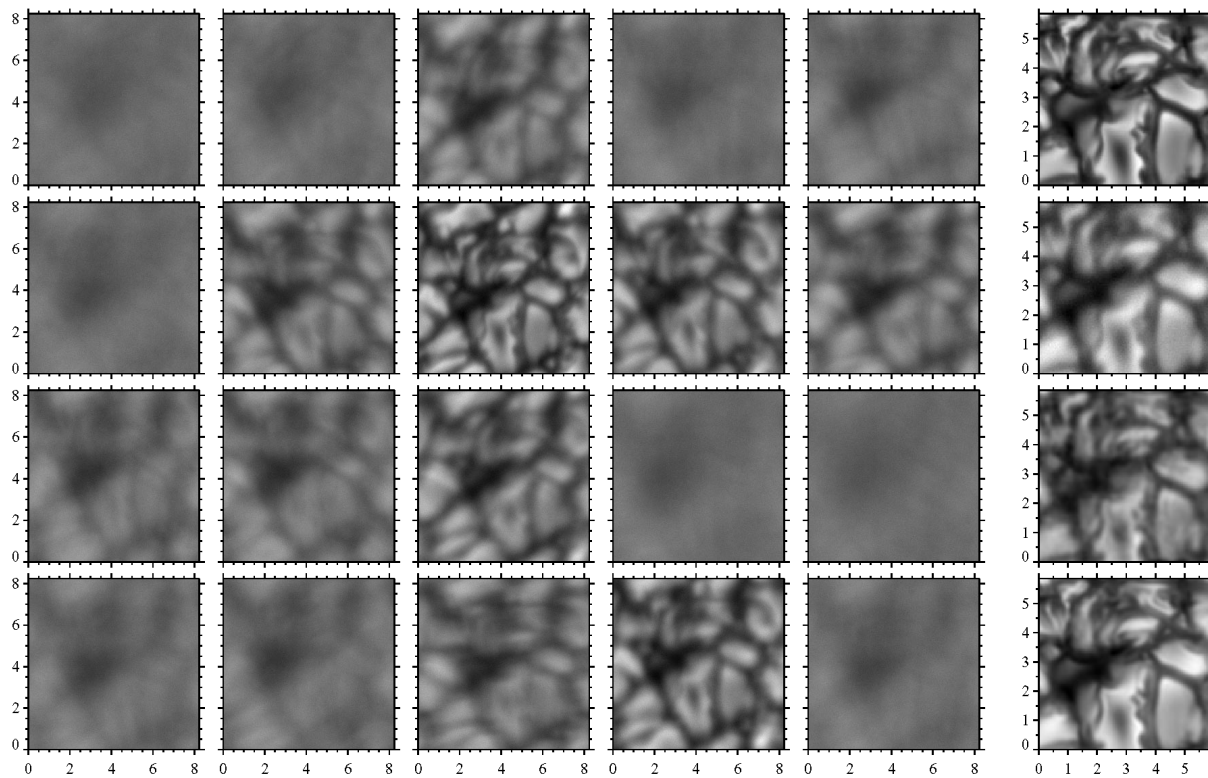


Fig. 9: Simulation of the feasibility of speckle reconstruction with a 140-cm telescope. First a computer generated 200-frame burst has been created with $r_0 = 10$ cm. The 20 frames at left show every 10th frame of the series. Then the four images at right show respectively: the original solar scene, the best frame (which is equal to image number 8 at the left, however on a different scale), the result of speckle reconstruction using the full burst, and the result of speckle reconstruction combined with a low order adaptive optics system.

The original image comes from a Nordlund & Stein simulation which closely matches solar granulation. It has appropriate numerical resolution (24 km cell size) and contains details at scales corresponding to the $0.07''$ diffraction limit. The seeing spoiled image was generated by C.U. Keller (NSO Tucson). His code applies a pupil phase screen with a Kolmogorov spectrum with $r_0 = 10$ cm. Shot noise was added corresponding to the well depth of the DOT cameras. The images at right cover a smaller area because of image motion. The third image on the right results from feeding the simulation to the DOT speckle code by Sütterlin (Utrecht University). The fourth image is similar but with a low order 37 actuator AO system included.

6. CONCLUSIONS

We presented our plans to increase the DOT from 0.45m to a 1.4m DOT++ by replacing the optical system, mirror support and telescope top, and keeping the present DOT telescope mount, tower, tent enclosure, multi-wavelength- and speckle system. Because much of the current DOT will be used, the costs are relatively low.

The upscaling includes a new optical design which permits a user selectable choice between angular resolution and field size, as well as transversal pupil shift introducing the possibility to use obstruction free apertures until 65cm. Based on DOT seeing statistics and simulations we showed that we expect diffraction limited performance in moderate seeing conditions with the combination of a low order AO system, which improves the speckle S/N substantially.

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