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GISOT: A giant solar telescope

Robert H. Hammerschlag[*a], Oskar von der Lühe[b], Felix C.M.Bettonvil[a,c],
Aswin P.L. Jägers[d], Frans Snik[a]

[a]Astronomical Institute, Utrecht University, Princetonplein 5, 3584CC Utrecht, the Netherlands
[b]Kiepenheuer-Institut für Sonnenphysik (KIS), Schöneckstrasse 6-7,
79104 Freiburg i.Breisgau, Germany
[c]Netherlands Foundation for Research in Astronomy (ASTRON), P.O.Box 2,
7990AA Dwingeloo, the Netherlands
[d]Instrumental Group Fysica (IGF), Utrecht University, Sorbonnelaan 4,
3584CA Utrecht, the Netherlands

ABSTRACT

A concept is presented for an extremely large high-resolution solar telescope with an aperture of 11 m and diffraction limited for visual wavelengths. The structure of GISOT will be transparent to wind and placed on a transparent stiff tower. For efficient wind flushing, all optics, including the primary mirror, will be located above the elevation axis. The aperture will be of the order of 11 m, not rotatively symmetrical, but of an elongated shape with dimensions 11 x 4 m. It consists of a central on-axis 4 m mirror with on both sides 3 pieces of 2 m mirrors. The optical layout will be kept simple to guarantee quality and minimize stray light. A Coudé room for instruments is planned below the telescope.
The telescope will not be housed in a dome-like construction, which interferes with the open principle. Instead the telescope will be protected by a foldable tent construction with a diameter of the order of 30 m, which doesn't form any obstruction during observations, but can withstand the severe weather circumstances on mountain sites.
Because of the nature of the solar scene, extremely high resolution in only one dimension is sufficient to solve many exciting problems in solar physics and in this respect the concept of GISOT is very promising.

Keywords: solar telescope, high resolution, seeing, telescope optics

1. INTRODUCTION

The first pictures from the 1 m Swedish Solar Telescope (SST)[1,2] obtained in 2002 show the solar surface with an unprecedented resolution of 0.1 arcsec, revealing a new world to solar astronomers in the realm of fine structure. However, it is evident even from these pictures that there is still a wealth of phenomena to study in the solar atmosphere which remains unresolved even for the SST. Therefore, the development of larger telescopes such as the 1.5 m GREGOR telescope[3] up to the 4 m Advanced Technology Solar Telescope[4] is being pursued. They will provide a resolution of 0.07 and 0.03 arcsec, respectively, at visible wavelengths. These projects are conceptually mature and scientifically soundly justified.

When asking the question which kind of telescope would make the ultimate high-resolution observation of the Sun from Earth, a desired resolution of 0.01 arcsec, corresponding to some 10 km on the solar surface, keeps reappearing. It is believed that a scale of 10 km would represent the limit observable fine detail in the stellar atmosphere, limited by radiative transfer and scattering processes. Clearly, physical processes at even smaller scales do exist, such as turbulent flows, interfaces between regions of differently magnetized plasma, current sheets in chromosphere and corona, and the like. It is doubtful whether these processes produce spatial or spectral signatures that are accessible to remote sensing.

[*] R.H.Hammerschlag@astro.uu.nl; phone and fax +31 30 2535220; http://dot.astro.uu.nl

We have asked the question how a telescope that is capable to make observations at these extreme scales - i.e. the "OWL of solar physics" - would look like. The answer is clearly a significant step beyond ATST, because baselines of the order of 10 m are required. The collected power of a conventional telescope with a 10 m aperture poses a tremendous problem. Previous studies of telescopes of this size thus involve annular apertures or dense interferometer arrays with much reduced collecting areas[5,6]. The problem here is that a large structure or complex optical configurations are needed.

We are proposing here a compact solar telescope with an elliptically shaped aperture, which provides baselines of 11 m in one direction and 4 m in the other. The telescope is intended for a spectral region covering the near-UV to the near-IR (380 nm to 2200 nm) and will provide diffraction-limited resolution along the 11 m baseline of 0.01 arcsec in the blue to 0.04 arcsec at 1.6 microns. The resolution in the other direction will be 0.03 and 0.12 arcsec. The telescope is mounted in an alt-azimuth fashion with the long baseline in the horizontal direction, keeping the profile low. Therefore, the orientation of the elliptical point-spread function (PSF) in heliographic coordinates is a function of the solar hour angle.

The scientific reason for accepting an elliptical PSF that cannot be oriented at will is that while essentially all small-scale processes show a preferred orientation, their general statistical distribution is isotropic. For a given phenomenon, it should always be possible to find an instance whose orientation agrees favourably with the orientation of the PSF for a given observation.

In the following sections we will discuss the optical layout, seeing and open principle, and the mechanical setup to overcome the problems to get this extremely high resolution with affordable technology. Finally, we will give some conclusions about the design.

2. OPTICAL LAYOUT

The proposed aperture shape is elliptical with a long axis of 11 m and a short axis of 4 m. It is not a single dish, but a mosaic of several mirrors (Fig. 1a). All composing mirrors have a circular shape. There is a central axial mirror of 4 m diameter and six off-axis mirrors of 2 m diameter. This configuration has several significant advantages. All mirrors are relatively easy to make without special polishing problems. Hence, the shape and smoothness of the surfaces can be of extremely high quality, which is a big advantage for high-resolution work. The round shape of the individual mirrors avoids undesirable edges in the PSF. Fig. 1b shows a grey scale intensity plot of the PSF, Fig. 1c shows a 3-D diagram of this function, Fig. 1d shows a cut along the high resolution 11 m direction and Fig. 1e shows a cut along the 4 m direction.

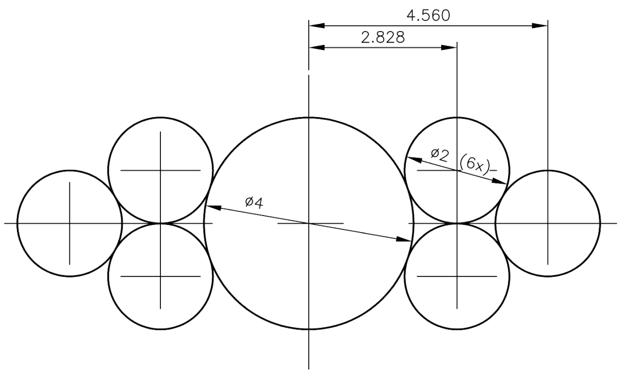


Fig. 1a. Aperture shape 1 consisting of a central axial mirror with 4 m diameter and six off-axis mirrors with 2 m diameter, which form together an approximately elliptical shape of the aperture.

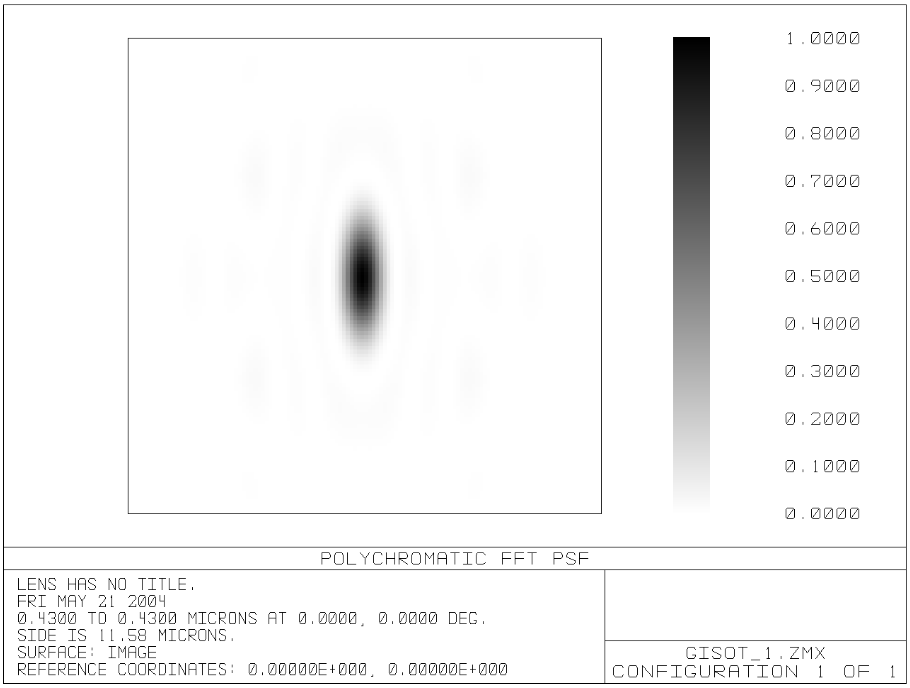


Fig. 1b. Intensity plot of the point-spread function of aperture shape 1.

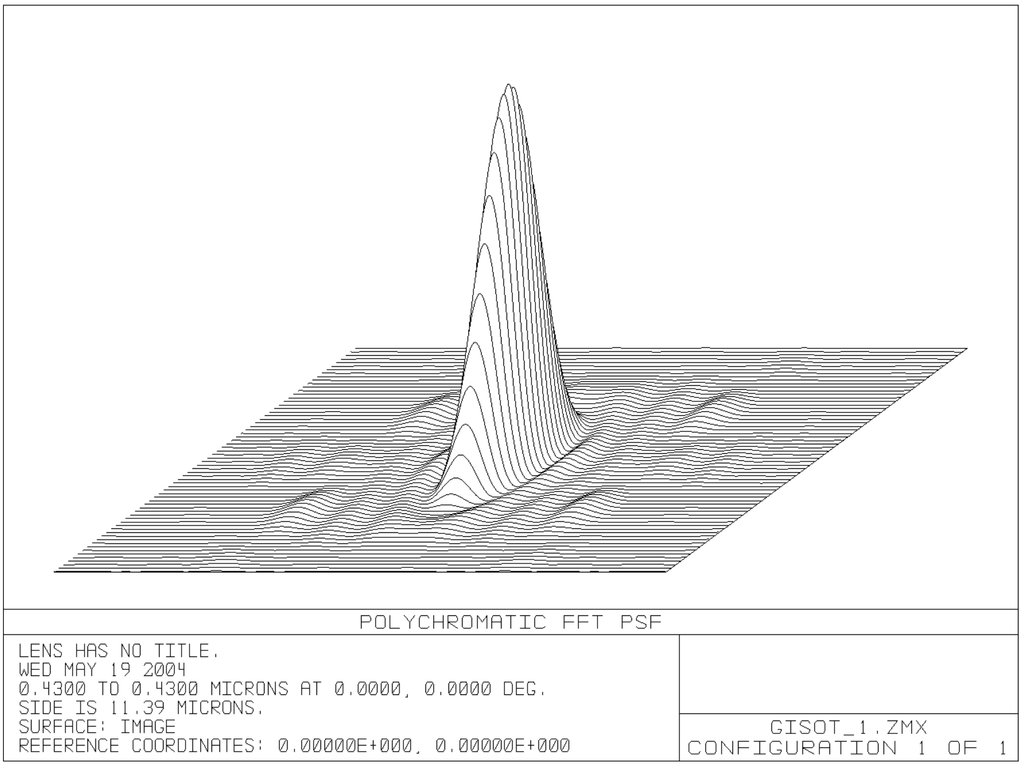


Fig. 1c. 3-D diagram of the point-spread function of aperture shape 1.

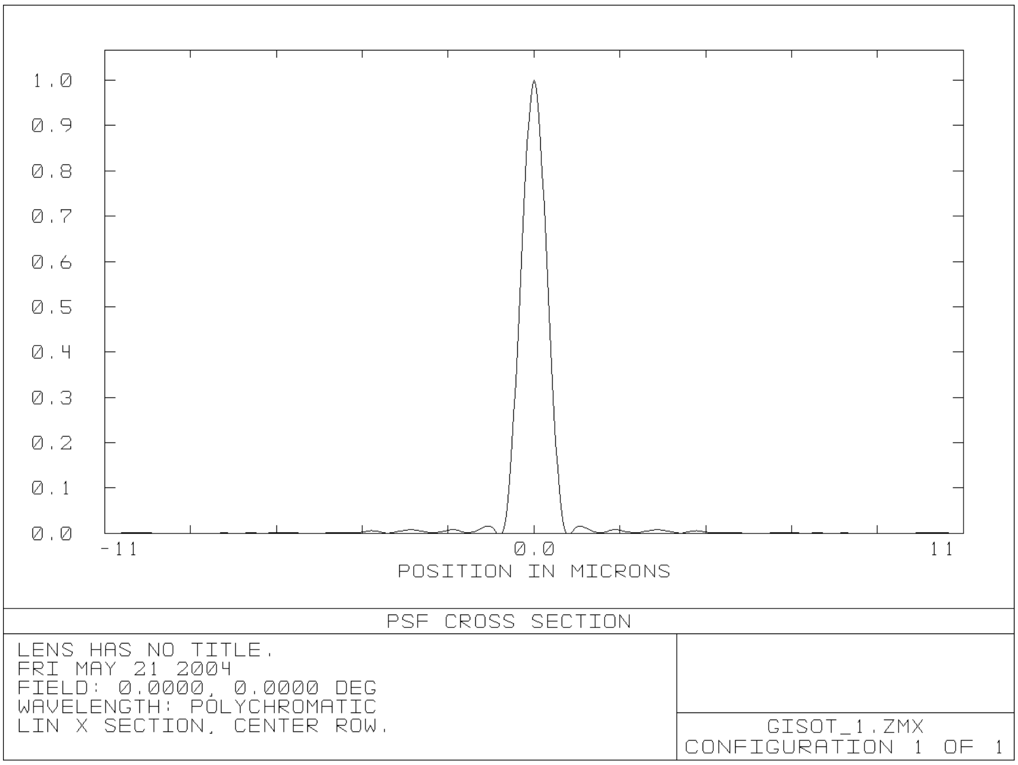


Fig. 1d. Cut along the highest resolution 11 m direction of the point-spread function of aperture shape 1.

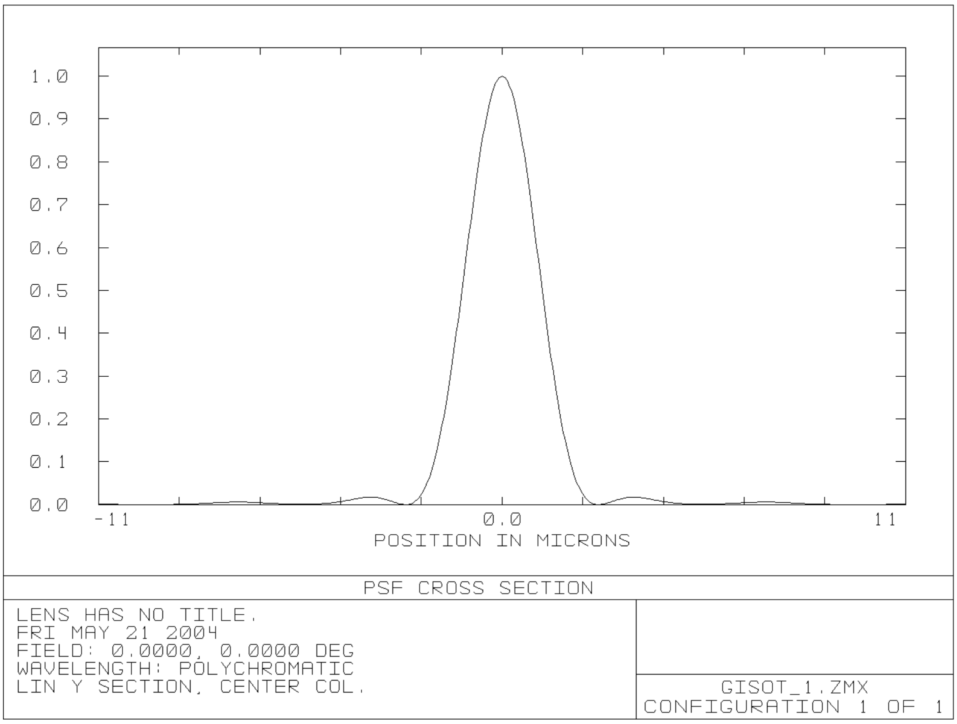


Fig. 1e. Cut along the 4 m direction of the point-spread function of aperture shape 1.

The mirrors are of the lightweight type, which means triangle shaped hollow spaces, with openings on the backside of the mirrors. The radial supports of the mirrors in their gravity plane are incorporated in these hollow spaces. Consequently, no radial support system outside the rim of the mirrors is required and they can be placed next to each other, filling the elliptical aperture shape, which is essential for a good PSF. In addition, the circular shape of the individual mirrors permits a very precise shape till the utmost rim of the mirror, which is essential to reach the highest possible resolution. The hollow spaces can also be used to place a closed air-cooling system to keep the temperature homogeneous over the whole mirror.

A diffraction-limited PSF like the one shown in Fig. 1 is possible only if all elements of the primary mirror assembly form a parabola with a precision of a small fraction of the wavelength for the entire altitude range. There are three steps required to achieve this, each of which forms a control loop:

1. Removal of residual aberrations from the optical elements and aberrations due to atmospheric turbulence from each element of the assembly. This requires an individual adaptive optics system for each element. The central mirror needs an adaptive optics system, which is comparable to that of the ATST while the remaining six mirrors need systems, which are about four times smaller. While all of these are systems of considerable complexity, it is safe to consider them not as show stoppers given the present progress in solar adaptive optics development.
2. Co-alignment of the image from all elements to a precision of the order of the full resolution of GISOT. This requires high-precision pointing control of each of the elements of the primary mirror, as well as a pointing detection system. The latter can be based on current solar adaptive optics wave front sensor technology and should not present a fundamental problem.
3. Co-phasing of the primary mirror elements, i.e. the control of their relative axial position or the "piston error". This requires high precision axial control of the elements of the primary mirror, as well as a very stiff axial mechanical mount, and a suitable sensing method. Common adaptive optics wave front sensor technology based on e.g. the Hartmann-Shack principle are incapable to measure piston error, an interferometric method involving all elements is required.

There are several options for realizing the co-phasing. One would use several white-light Michelson interferometers on areas where two elements of the primary touch. There are ten such locations for the measurement of six piston differences, which should be sufficient for a robust control system. Another possibility would involve an interferometric test at the center of curvature, which would require Null optics and a stiff attachment to the telescope tube. None of these two methods would be able to also detect the piston error caused by atmospheric turbulence, which could easily amount to ten waves at one micron. One method to also detect atmospheric piston would be a modified version of the Damé[7] interferometer, which derives the piston error directly from sunlight. The modification would involve feeding broadband light from a small common field into optical fibers, one for each primary element. A multimode fiber is used for the central mirror and single mode fibers for each of the six outer mirrors. The light of the multimode fiber is splitted six fold and is mixed with the light of the single mode fibers, resulting in six interferograms delivering the control signal. A separate metrology system is needed to monitor the length of the fibers. The complexity of such a sensor is comparable with the FINITO fringe tracker for the ESO VLT Interferometer.

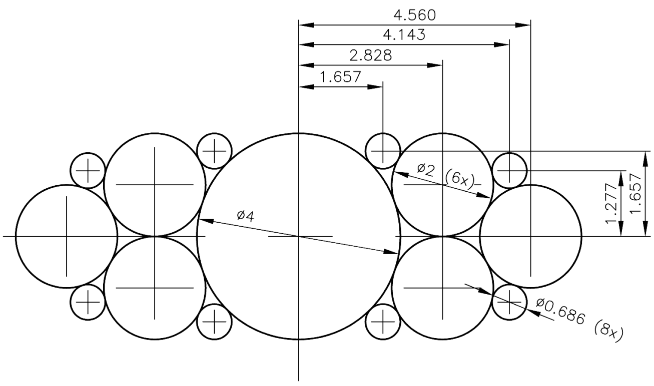


Fig. 2a. Aperture shape 2 with eight additional smaller mirrors to fill the gaps on the rim of the elliptical aperture shape.

High precision axial control of the primary mirror elements as well as a very stiff mount can be reached in the following way. In a point of contact both mirrors are supported by the same stiff element. A fine adjustment between both mirrors is incorporated in the element. The basic principle is a stiff short bar of which the length is changed by an adjustable

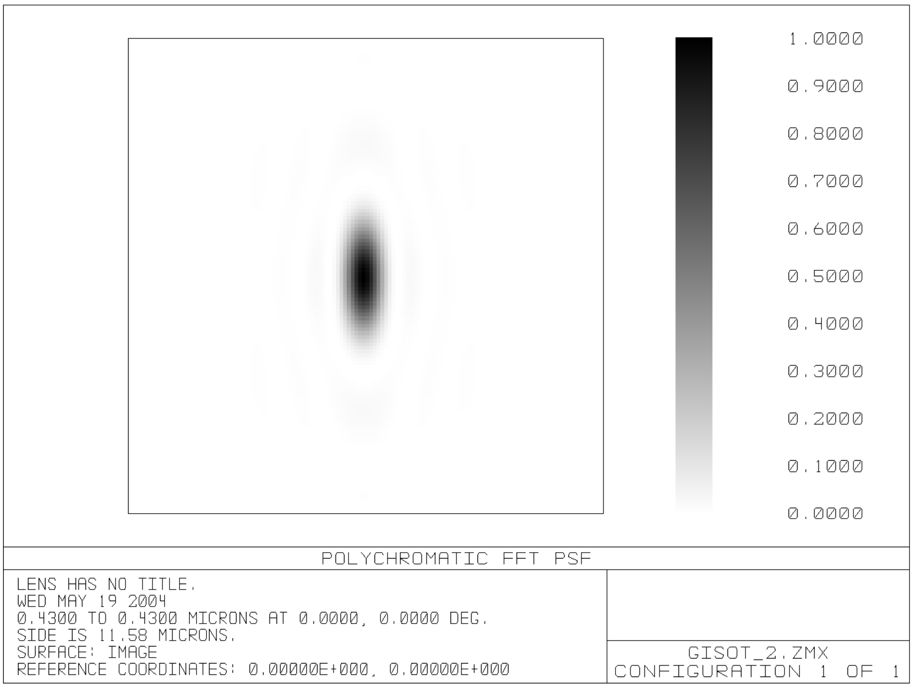


Fig. 2b. Intensity plot of the point-spread function of aperture shape 2.

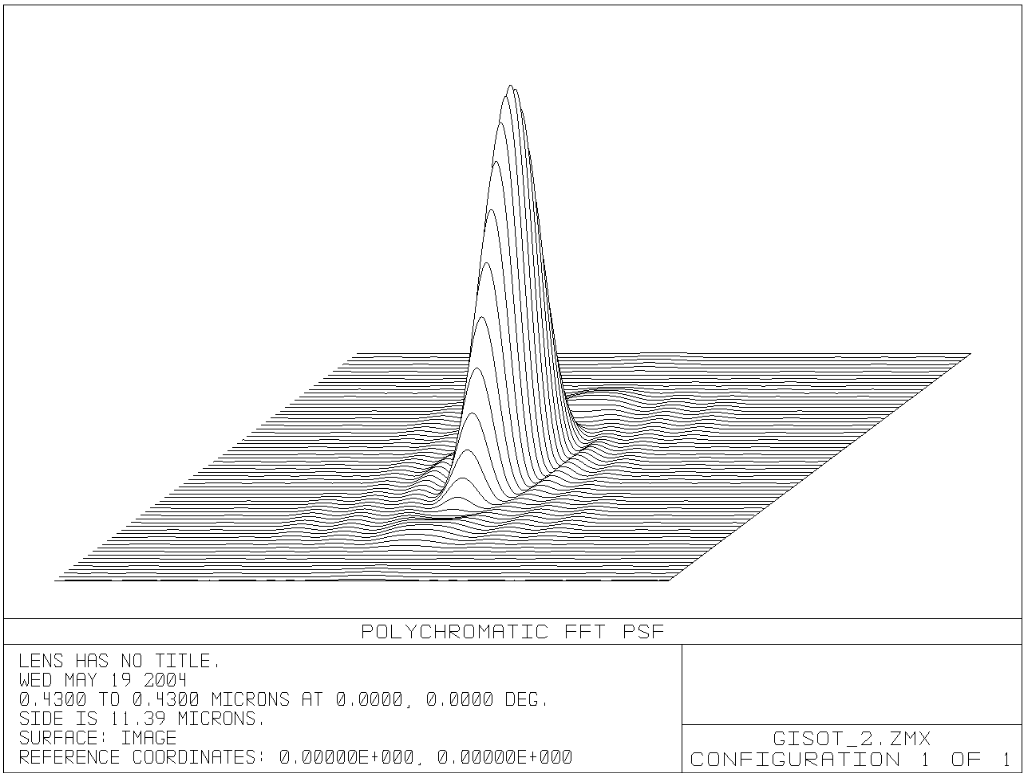


Fig. 2c. 3-D diagram of the point-spread function of aperture shape 2. Decrease of diffraction light hills compared to aperture 1.

force, for instance a disc spring. The spring is tensioned by hand or by a small motor, which is only powered during adjustment. There is no creeping effect. An adjustment element can work in more than one direction. The stiff parts that determine the position between the two mirrors can be produced of the same ceramic materials as the mirrors with low or neglectable thermal expansion. Adjustments within nm-precision are possible. A detailed description with drawings is outside the scope of this paper. In conclusion, the mirror mount deviates from classical designs; from a mechanical

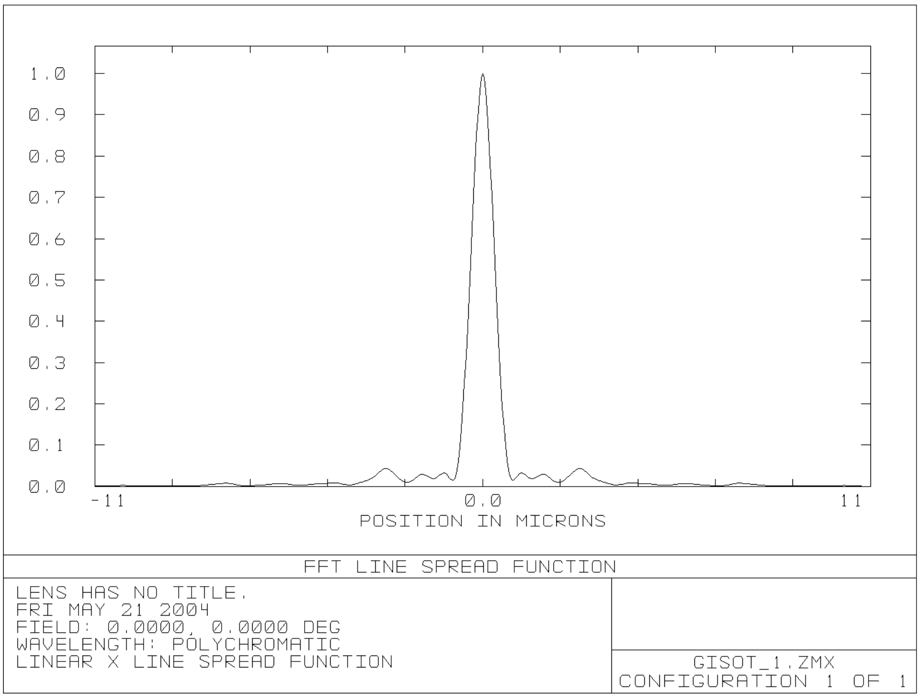


Fig. 3a. Integrated curve in the highest resolution 11 m direction of the point-spread function of aperture shape 1.

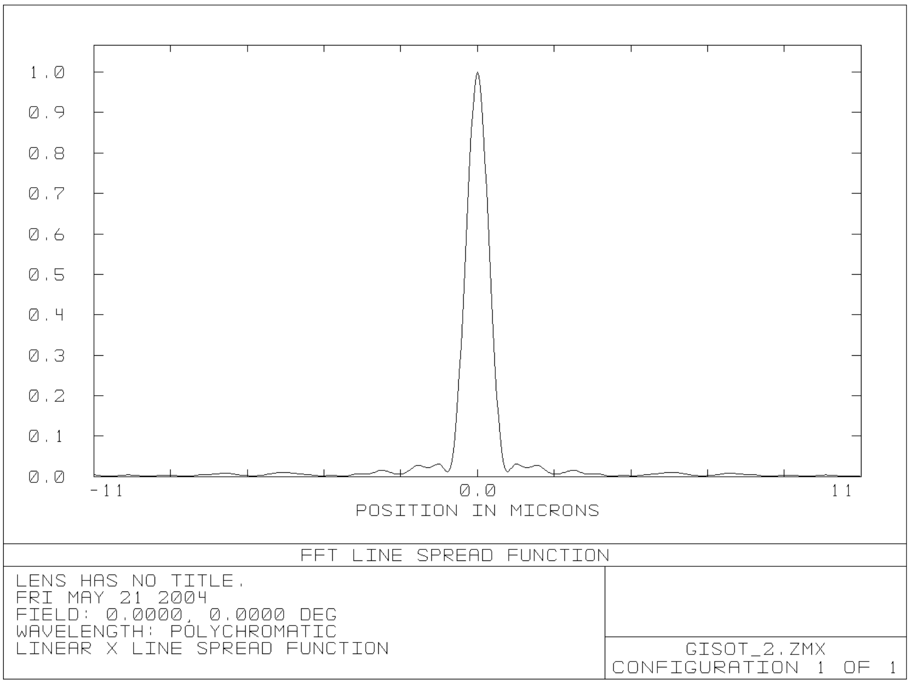


Fig. 3b. Integrated curve in the highest resolution 11 m direction of the point-spread function of aperture shape 2.

point of view, it connects together the individual mirrors into a single large dish. Ceramic elements of the same material as the mirrors are used to reduce temperature effects. Even a complete ceramic framework belongs to the possibilities.

An improved filling of the elliptical aperture shape is shown in Fig. 2a. Added are eight smaller mirrors - also with a circular shape – which fill the gaps on the rim of the elliptical shape of the aperture. Fig. 2b shows the grey scale

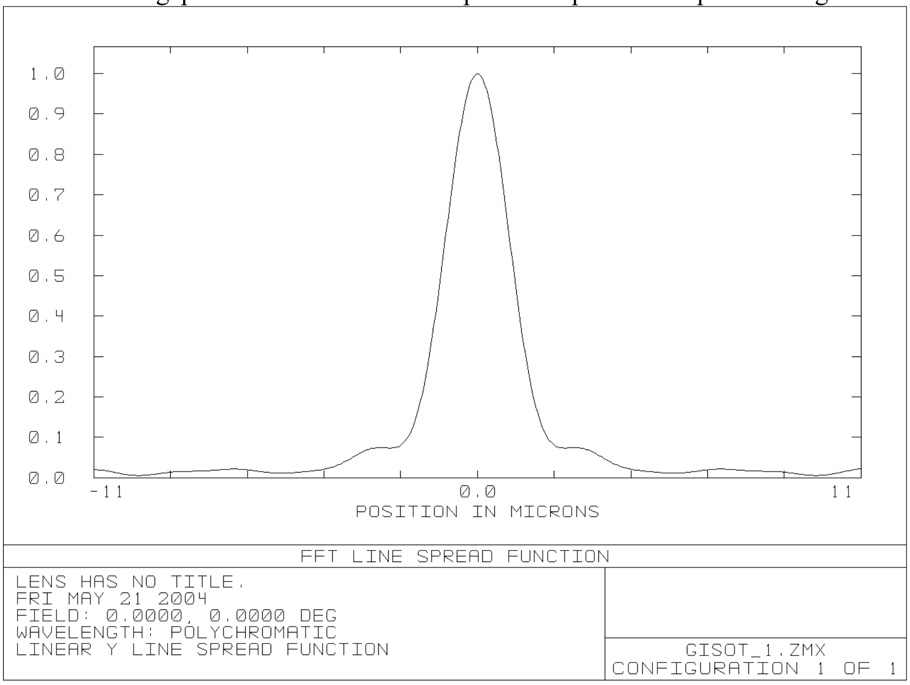


Fig. 4a. Integrated curve in the 4 m direction of the point-spread function of aperture shape 1.

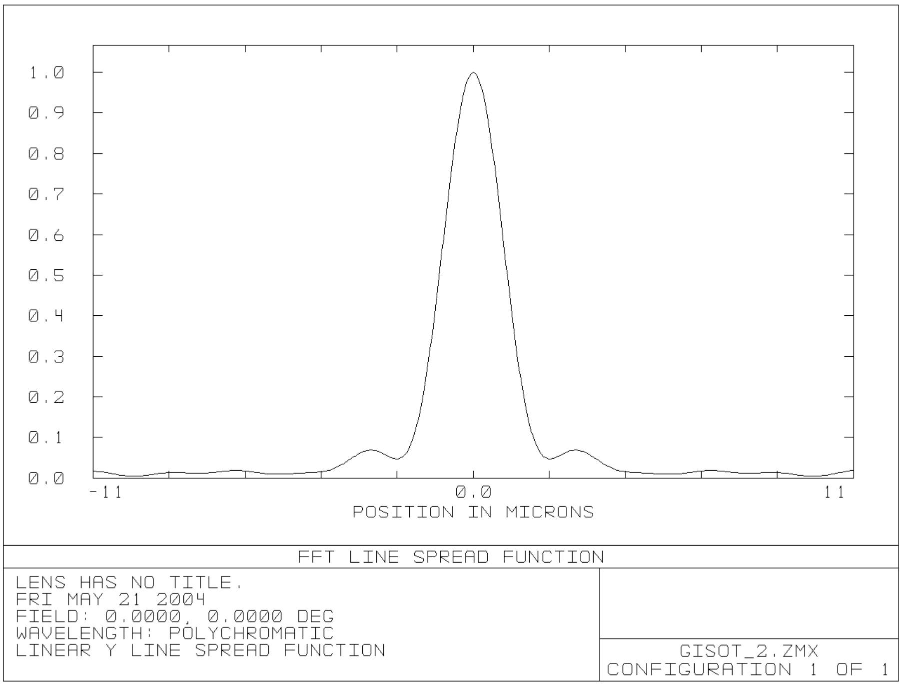


Fig. 4b. Integrated curve in the 4 m direction of the point-spread function of aperture shape 2.

intensity plot of the PSF and Fig. 2c shows the 3-D diagram of this function. There is less diffraction light outside the central peak due to adding the eight smaller mirrors. Comparison of the 3-D diagrams in Figs. 1c and 2c shows the decrease of diffraction light hills in Fig. 2c, particularly in the high resolution and in the oblique directions. A quantitative comparison of the diffraction light outside the central peak is possible with integrated curves. Fig. 3 shows the integrated curves in the high resolution 11 m direction: Fig. 3a for the aperture without the eight additional smaller mirrors, Fig. 3b for the aperture with the latter. Fig. 4 shows in the same way the integrated curves in the 4 m direction. The reduction of intensity in the side lobs due to the addition of the smaller mirrors is evident. For solar observations this reduction of light is important because of the occurrence of fine dark details with low contrast in a bright field. The improvement of the image quality is also demonstrated by the Modulation Transfer Functions (MTF).

Fig. 5a shows the MTF in the 11 m and 4 m directions in one graph for the aperture without the eight smaller mirrors and Fig. 5 b shows the same for the aperture with the latter.

The secondary optics consists of a water-cooled diaphragm, a second parabolic mirror and two flat mirrors (Fig. 6). These components form a very compact unit because of the short focal length of the second parabolic mirror of about 500 mm, depending on further optics behind the primary mirror. The setup of the secondary optics is similar to the one of the secondary optics of the DOT++[8].
In our further discussion we will use the following numbers:
Focus length of the primary mirrors 18500 mm
The f-ratio over the high resolution direction becomes 18500 / 11120 = f / 1.66

This is not an extremely high value and corresponds with the f-ratio of the DOT++. This moderate f-ratio ensures that the optics can be made with the excellent precision, which is necessary for high-resolution work. On the other hand, a focal length of 18500 mm is mechanically feasible, as we will see in section 4.

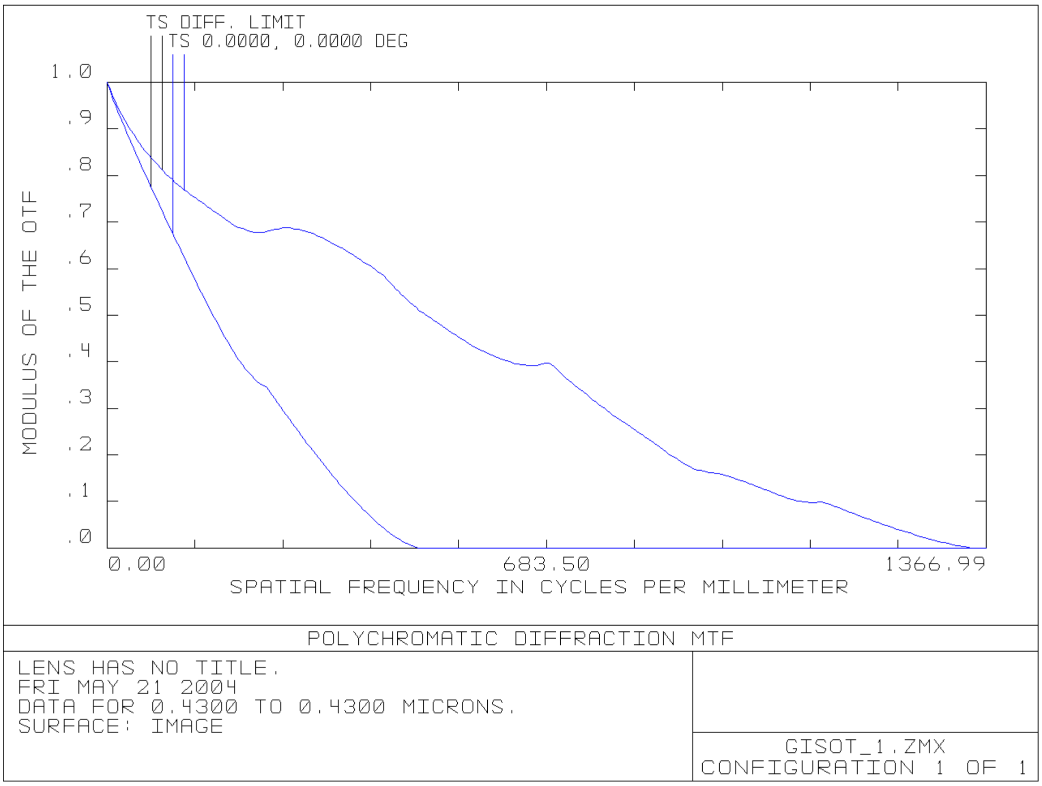


Fig. 5a. Modulation Transfer Function in the 11 m and 4 m directions of aperture shape 1.

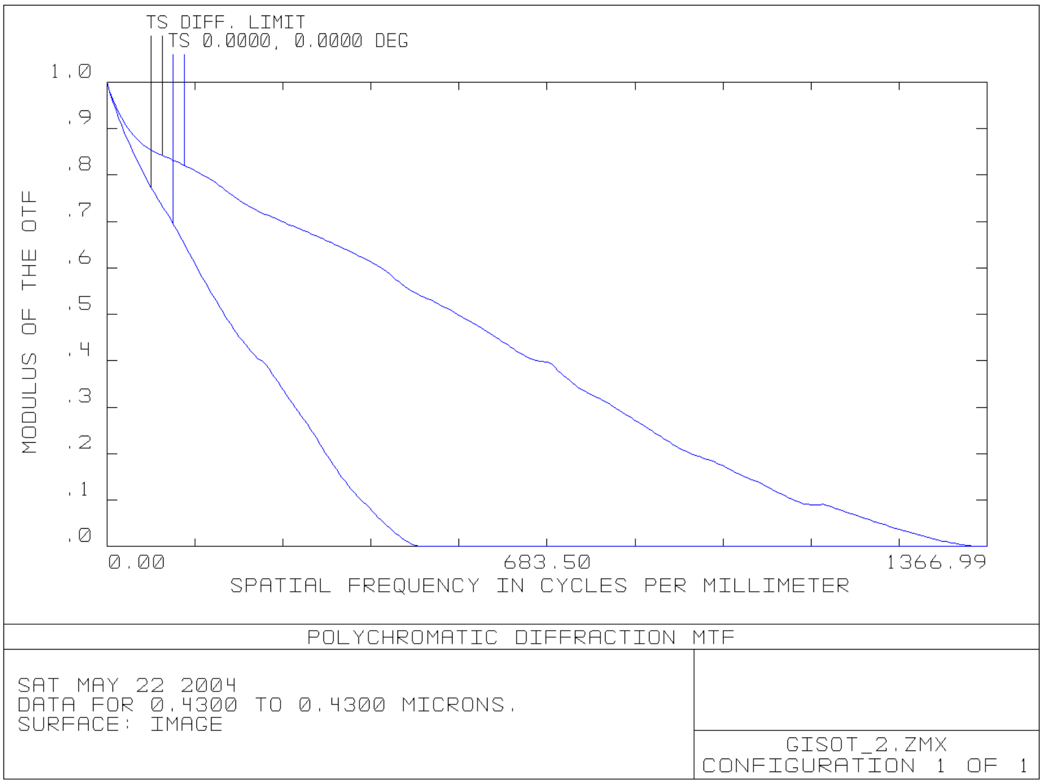


Fig. 5b. Modulation Transfer Function in the 11 m and 4 m directions of aperture shape 2.

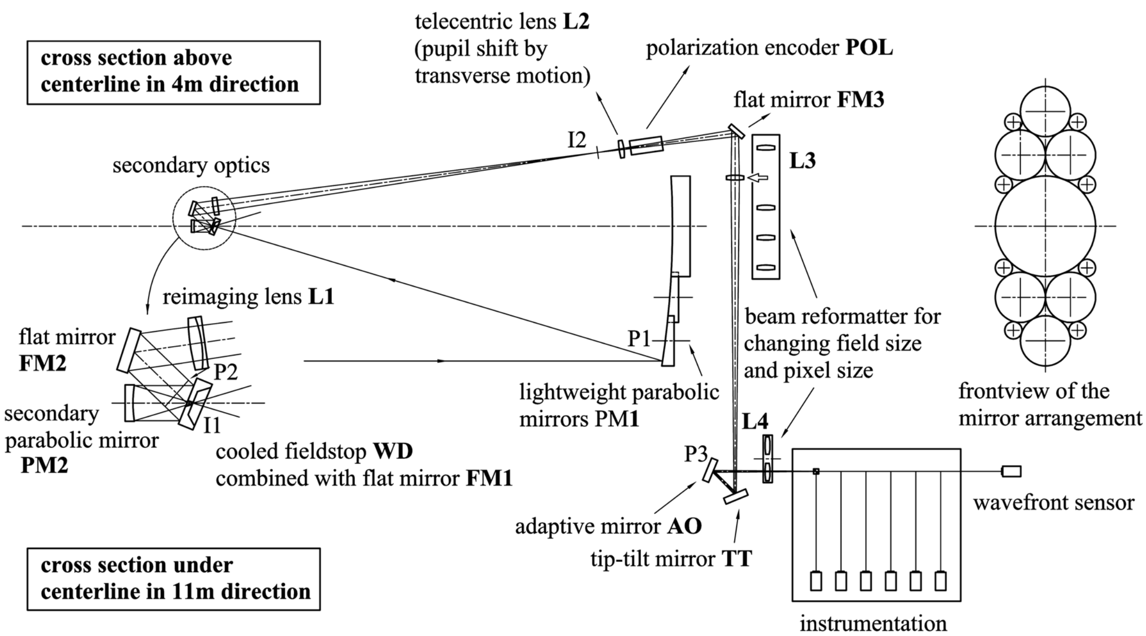


Fig. 6. Optics scheme (not drawn to scale).

The diameter of the hole in the water-cooled diaphragm is 16 mm, which corresponds to a field of 3 arcmin on the solar surface. The focal length of the secondary parabolic mirror is 500 mm and the diameter is 340 mm, of which 317 mm is used by the light. With these numbers the light concentration on the secondary mirror is equivalent to $(37/10)^2 = 13.7$ times normal solar light. From experiences with the DOT[9] and experiments in the light beam of the Swedish Telescope on La Palma we know that this concentration of light does not degrade the secondary optics. Air suction in the region around prime focus avoids schlieren.

The focal length of the secondary mirror is very short compared to nighttime telescopes. This is possible because of the small field of view. The diameter of the secondary beam becomes so small that we can use a re-imaging lens L1 (Fig. 6) after the secondary parabolic mirror. The latter can give a parallel beam giving full correction of coma and spherical aberration. Lens L1 is a weak lens with focal length of 16000 mm, f/47, which is not difficult to design for a broad wavelength range.

The central obscuration caused by the secondary optics is only 400 x 800 mm. This small obscuration permits the excellent use of the central 4 m mirror alone.

Near the image plane I2 the lens L2 images the entrance pupil to infinity. Consequently, behind L2 there is a telecentric region suitable for instrumentation like a polarization encoder.

In addition, a transverse shift of L2 shifts the pupil, which enables off-axis pupil selections. The effective aperture can be changed by pair-wise changing L3 and L4. Different L3 lenses, chosen from a selection box, produce different enlargements of the entrance pupil. The corresponding lens L4 keeps the final image plane on its place in the instrumentation box. The design has the unique feature that the pixel size (in arcsec on the sky) automatically scales with the diffraction limit defined by the selected effective aperture.

The design incorporates a tip-tilt mirror TT and an adaptive optics mirror AO in an optical setup similar to the system in the SST. To reach maximum sharpness a combination of AO with Speckle masking reconstruction is attractive, like is planned for the DOT++[8].

The advantage of the use of lenses is the possibility of a compact design of the tertiair optics in the telescope framework. Without doubt setups with only mirrors are possible, but use more optical components and longer light paths than the lens setup given here. Also optical setups for image transport to a Coudé room under the telescope are possible without problems.

3. SEEING AND THE CHOICE OF THE TELESCOPE DESIGN

Solar observations are made during daytime. The solar light heats the ground and all structures. When the weather is completely calm – no wind at all – experiences have shown that there are so many warm air plumes, that the seeing is bad and consequently no high-resolution observations are possible. Simple calculations show, that temperature deviations of 0.1° C within the air of a cross section of the incoming light beam already disturb the image.

However, a light breeze of only a few meters per second improves the situation drastically. The wind removes the plumes of warm air. The first telescope, which exploits this phenomenon also for the light beam inside the telescope, is the Dutch Open Telescope (DOT).[9]

All other existing high-resolution solar telescopes use an evacuated light path for the primary beam inside the telescope. The best evacuated telescope to achieve high resolution is without doubt the SST[1,2]. It uses a singlet lens as entrance window for the vacuum chamber. The diameter of this special homogeneous fused silica lens is 1 m.

For significantly larger light beam diameters the entrance window for the evacuated light path inside the telescope is technically not possible. Here the DOT, with its mirror of a diameter of 0.45 m, has shown the feasibility of an open light beam flushed by the natural wind. The DOT is unsurpassed in the production of high-resolution films with a constant diffraction limited quality over hours; see the DOT movies on http://dot.astro.uu.nl . The DOT observations on La Palma have shown that a wind velocity of only a few m/sec is enough to get excellent images. The right wind direction is more important than the wind speed. This result is in accordance with seeing measurements on La Palma. A second telescope relying on flushing by natural wind will be the GREGOR[3] with a mirror of a diameter of 1.5 m, see http://gregor.kis.uni-freiburg.de .

With the wind, air comes in, continually changing in temperature on a scale of seconds during daytime. The air temperature is much more variable than during nighttime. This makes a solution with a dome using temperature control much more difficult for a solar telescope than for nighttime telescopes. With a constant temperature inside the dome, there will still exist temperature differences in the air around the opening in the dome due to temperature fluctuations of the air during daytime. These temperature differences will cause image deterioration, even if the air inside the dome is cooler. The shear between outside and inside air will cause an exchange of air bubbles with different temperature.

As a matter of fact, all the successful vacuum solar telescopes (Dunn Solar Telescope, SVST, SST, VTT) are open telescopes from the viewpoint of dome-seeing: only a small obstruction, not much larger than the primary optical beam in a closely fitting vacuum housing, sticks into the open air.

As a consequence of all these experiences, we choose for GISOT an open primary beam relying on flushing by natural wind. Also telescope mount and tower will be open to reach the best possible local seeing circumstances.

A telescope operating without dome has to be stiff enough against wind forces. That such a construction is possible is proven by the DOT as well as by the SST. For a stiff design the choice of the right geometries is very important.[10] The appendix of the reference is devoted to principles for stiff constructions. These principles are used in the mechanical design of GISOT, which is described in the next section.

An alternative design for a large aperture solar telescope is a vacuum telescope with a mosaic of several smaller entrance windows of about 1 m diameter. The support structure for the windows has to permit a close arrangement of the windows because the PSF and MTF deteriorate rapidly when increasing the space between the rims of the windows. Hence, a study of this support structure is needed to answer the question of how close the entrance windows can be while keeping the required high optical quality of the entrance beams. Further disadvantages of such a setup are a large turret construction and a massive building, which will give more thermal disturbance of the surrounding air than the open concept construction. High resolution is the primary goal for GISOT and consequently we started with the study of an open concept.

4. MECHANICAL SETUP

The compact optical unit around the primary focus is kept in place by an open framework (Fig. 7). Despite the fact that the secondary optics collects the light of the whole elliptical aperture, its obstruction of the primary axial mirror of 4 m diameter is very small: only a few percent of the 4 m mirror. Also the spider construction of the open framework

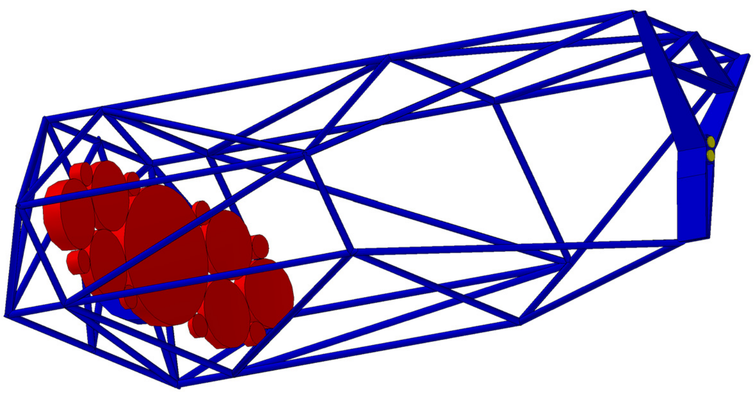


Fig. 7. Open framework structure of the telescope tube.

obstructs only a few percent of the 4 m mirror. Consequently, the 4 m mirror on its own is already a powerful high-resolution telescope.

The open framework telescope tube is placed in a fork, again of an open framework construction (Fig. 8). The fork is placed on an azimuth ring, which fits on the platform of an open tower (Fig. 9). The tower uses the principle of pure translation of the platform under wind load[11]. With special geometries this principle is maintained in a high tower of the order of 60 m, which consists of a number of stories and is built with normal framework techniques[12] (see section 2 of the reference).

The GISOT is protected by a completely open foldable tent construction, similar to the dome design of the DOT and GREGOR telescopes[12] (see section 3 of the reference). The dome for GISOT has a diameter of 30 m. Rough calculations show that the geometry used for the DOT and GREGOR dome is still very suitable for a diameter of 30 m. This geometry gives a maximum cloth span of 8 m between two bows in the case of a dome of 30 m diameter. Experts in the field of the known static membrane constructions confirm, that this span distance is well within the capability of the available cloth qualities. Span distances up to 15 m are quite normal. These experts are also positive about the possibilities to develop the bows and machine construction for large movable domes similar to the DOT and GREGOR domes.

The dome is connected to the tower platform with the help of a ring construction, which is organically incorporated into the tower design, such that the forces on the base ring of the dome do not disturb the pure translation of the platform points, where the telescope base construction is fastened.

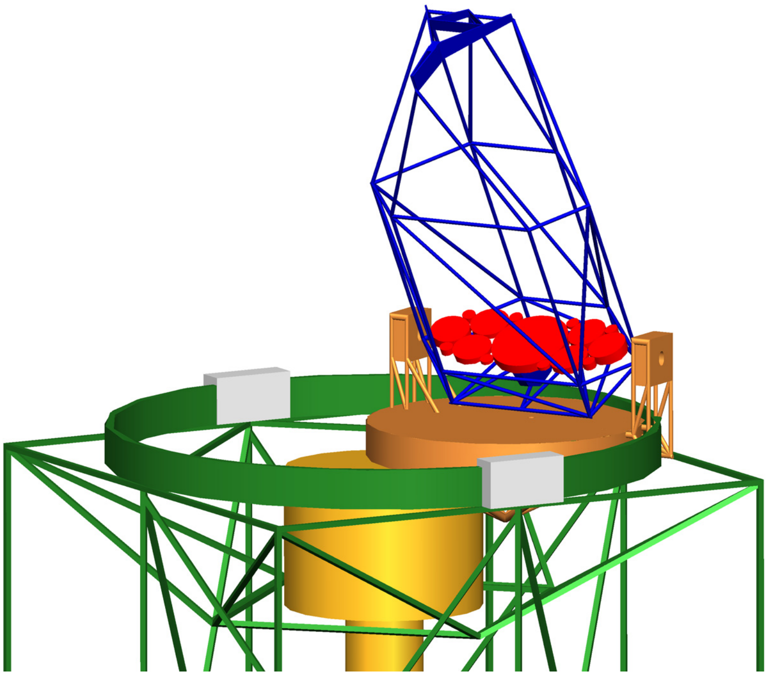


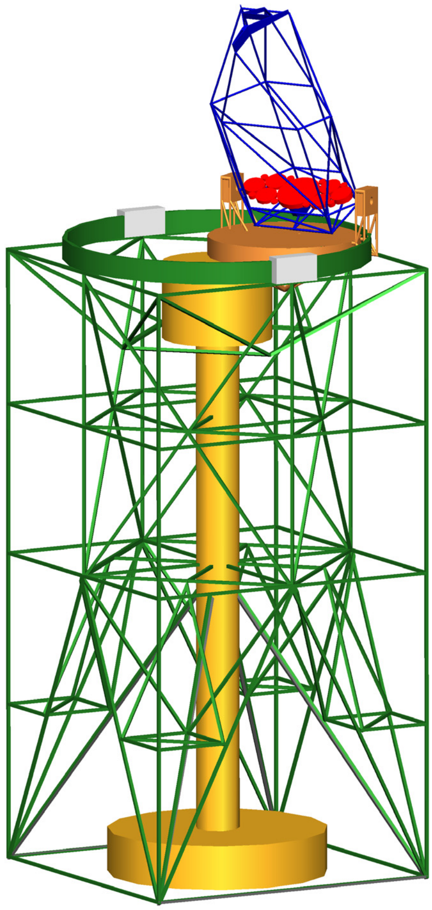
Fig. 8. Open framework of the whole telescope structure.

Under the center of the tower platform a closed Coudé room is planned. From the viewpoint of a stiff tower construction in the wind, the diameter of this closed Coudé room could be up to 20 m. However, from the viewpoint of best possible local seeing a smaller dimension is preferable, for instance 10 m diameter. It is a question of finding the best compromise between necessary space for instrumentation and no significant degradation of the local seeing. We propose to make under the platform an open framework in which experiments in closed rooms of several sizes can be placed.

Exactly at the center of the tower there is a closed shaft of about 5 m diameter with elevator, staircase or ladder and cables protected against all weather influences. Experiences with the SST – and earlier with the SVST – on the Swedish Tower on La Palma showed that a tower with 5 x 5 m cross section does not disturb substantially the thermal homogeneity of the surrounding air if there is a light breeze, which is anyhow necessary for high resolution solar observations, as discussed earlier in section 3. The principle is the following: with a light breeze the air has no time to get a deviating temperature if the obstructions are not too large in dimension. In this case we prefer the advantages of all weather protection above the marginal seeing advantage.

The wind force on the closed shaft does not disturb the parallel motion principle and hence the stability of the platform, because the connection with strips between shaft and platform cannot bring moments to the platform, it can only bring horizontal forces. These forces give no rotation to the platform when the shaft is at the center of the tower.

The shaft can be used for guidance of the secondary light beam to a second large Coudé lab on the ground. This is an attractive option for observations with instrumentation of large dimensions. For a small field of about 1 arcmin no additional optical components are necessary for the image transport over the distance of 60 m along the shaft. A vacuum tube around the light beam through the shaft belongs to the possibilities.



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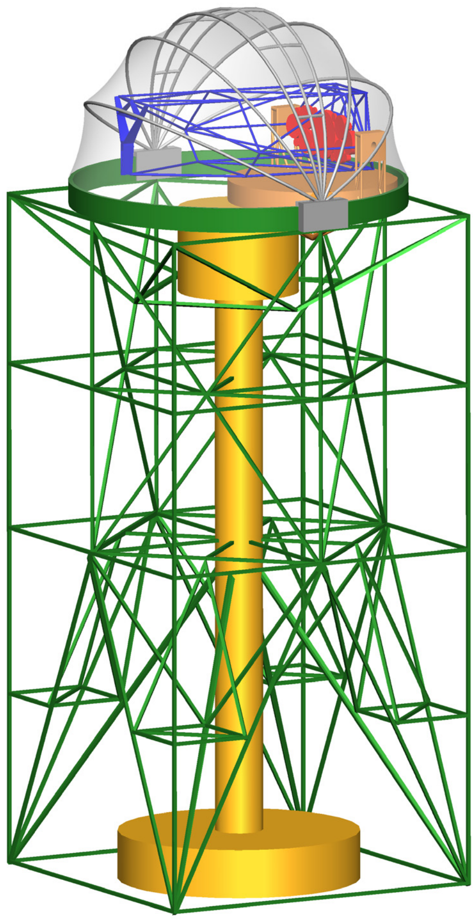

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Fig. 9a. Complete concept of the GISOT on an open tower.

Fig. 9b. GISOT parked and tent closed.

5. CONCLUSIONS

The presented mosaic configurations for an elongated aperture give surprisingly good PSFs and MTFs. This is due to the good filling of the surface and the absence of sharp corners. The remaining openings between the mirrors can be used for air suction.

The telescope design permits realization of the optics in phases. A start with the central mirror of 4 m diameter gives already a powerful high-resolution telescope. A next step is the addition of the four pieces of 2 m off-axis mirrors near the primary mirror, followed by the two pieces of 2 m mirrors at both ends of the elongated aperture. Finally, the eight smaller mirrors can be added.

One can ask whether the last step is worth its effort. There are two arguments: 1. On the solar disk small dark details are present with low contrast; these details are better resolved with less diffraction light outside the central peak of the PSF. 2. The effort necessary for the eight small errors is not large compared to the effort to construct a larger baseline of the telescope as a whole.

The open design makes use of the elongated shape of the aperture in an efficient way. The elongated aperture fits organically into the fork, which on its turn fits on the acentric azimuth ring on the platform. This acentric design allows a compact park position of the large telescope tube. In this way the overall size of the mechanical structure remains within affordable dimensions.

The telescope is specialized for high resolution; there are no compromises made which would reduce its function in that respect. This does not mean that GISOT cannot be used for a pretty broad range of other interesting observations. The mechanical setup permits easy exchange of the secondary optics and extension with many instruments. To unravel the processes on the solar surface, a GISOT is an indispensable addition to the instruments with an accent on universe usability.

ACKNOWLEDGEMENTS

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