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The 1-meter Swedish solar telescope

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ABSTRACT

We describe the 1-meter Swedish solar telescope which replaces the former 50-cm solar telescope (SVST) in La Palma. The un-obscured optics consists of a singlet lens used as vacuum window and two secondary optical systems. The first of these enables narrow-band imaging and polarimetry with a minimum of optical surfaces. The second optical system uses a field mirror to re-image the pupil on a 25 cm corrector which provides a perfectly achromatic image, corrected also for atmospheric dispersion. The adaptive optics system is integrated with the design of the telescope but is sufficiently flexible to allow future upgrades. It consists of a low-order bimorph modal mirror with 37 electrodes, allowing near-diffraction-limited imaging a reasonable fraction of the observing time on La Palma.

The new telescope became operational at the end of May 2002 and has already proven to be the most highly resolving solar telescope ever built. In this paper, we describe its mechanical and optical design, the polishing and testing of the optics and the instrumentation in use or planned for this telescope.

Keywords: Telescopes, optics, wavefront sensing, adaptive optics, Schupmann, solar physics

1. INTRODUCTION

The site of the SVST on La Palma is the best for solar telescopes of all presently known sites in the world. When in 1998 it became clear that the Large Earthbased Solar Telescope, LEST, would not be built, we started to investigate whether it would be possible to replace the existing 50-cm telescope with a new telescope of 1 meter diameter. At that time, the development of solar adaptive optics systems was making rapid progress, making it realistic to plan for a diffraction-limited 1-m solar telescope.

The conclusion of a preliminary design study[1] indicated that it would be possible to install a 1-meter telescope on the existing tower and that by re-using some of the design and instrumentation developed for the SVST, it would be possible to build an excellent such telescope within a budget of 2 M$.

In this paper, we describe the design, challenges and achieved performance of the 1-m solar telescope. Section two describes the conceptual design, Section three the mechanical design and Section four the design and tests of the optical system. Section five, finally, adds some concluding remarks.

2. CONCEPTUAL DESIGN

An early decision was that the priority of the new telescope was its scientific usefulness and a design that should be as simple and straightforward as possible. In order to avoid potential problems of open telescopes, such as telescope seeing, alignment problems and cleanliness of mirrors, it was decided to build an evacuated telescope that shared much of its design with the SVST, minimizing costs and risks.

The SVST used an achromatic doublet in the turret to form an image in the optics lab. A doublet of 1 meter diameter would be difficult to manufacture with high optical quality and would be diffraction limited over only 1/4 of the wavelength range compared to the doublet of the SVST. We therefore decided to use a singlet lens as primary image forming element and a Schupmann corrector, described below, for achromatic imaging or spectroscopy. The primary optical system of the NSST consists of only one singlet lens, acting also as vacuum window, and two flat folding mirrors.

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Figure 1 shows the layout of the tower with the turret, the vacuum system, the Schupmann corrector with its field mirror and the re-imaging optics, located on the optical table in the observing room.

3. MECHANICAL DESIGN

Initially, it was hoped that the turret design of the SVST could be scaled up and re-used in the new design but objections were raised against that. The main objection was that the SVST bearing system was over-determined by using both a bearing and three rollers for its azimuth and elevation axes.[2, 3] The SVST relied on friction drive on one of these rollers and since this had some problems, the decision was to instead use stiff roller bearings from Hoesch Rothe Erde together with a conventional gear system.

Another concern with the SVST turret design was that it is not overly compact and that scaling it up by a factor two could give problems with large torque from wind-load, which is 8 times larger with a telescope that is scaled up linearly by a factor two. Efforts were therefore called for in making the turret as compact as possible.

It was obvious also that a new mirror support system had to be designed for the two 1.4 meter turret mirrors. The only part of the SVST design that could be re-used in the new telescope was the mounting of the combined singlet lens and vacuum window, all other aspects of the turret required re-design.

3.1. Turret

The major concern in the design of the turret was adequate stiffness to ensure small pointing errors from wind-load and a high resonance frequency to minimize the risk of wind-induced vibrations while allowing the telescope servo system to operate with relatively high bandwidth. The critical points in the design were the stiffness of the bearing, gear and transmission system, the conically shaped fundament supporting the telescope and the mounting of the azimuth counter weight. In order to ensure a stiff design, a finite element (FE) model of the telescope and the roof of the tower was made by HighTech Engineering in Stockholm, based on a preliminary design (see Fig. 2). The FE analysis included a detailed model of the bearings and transmission system. This analysis revealed that the transmission system was too weak, yielding a 5 Hz resonance frequency and a 6 arcsec deflection under 15 m/s windoload. Re-design of this part increased the stiffness of the transmission system by more than a factor 15 that increased the first resonance frequency to 12–15 Hz, as measured with the telescope on the tower, and deflections from wind-load of less than 1 arcsec with 15 m/s winds. The FE analysis lead to improvements also in the fundament and the mounting of the azimuth counter weight.

The high stiffness needed for the gear and transmission system as well as the need to avoid inducing high-frequency pointing errors, required a high-quality gear system with detailed specifications of the teeth profiles for the big gear and its pinion. Subcontracting this work was done to a specialized firm (Flender Bocholt in Holland) with excellent result. This work was masterly and meticulously supervised by Robert H. Hammerschlag.

Another difficult and critical part of the design was the 1.1 meter large rotating vacuum seals. Repeated discussions and detailed instructions from the manufacturer (Advanced Products in Belgium) allowed the design and machining tolerances to be specified such that no problems with vacuum leaks have occurred in spite of the sometimes hostile weather conditions on La Palma at 2400 meters altitude. In fact, vacuum leaks are much smaller than was the case with the SVST. By pumping continuously, it is possible to reach a vacuum of 0.2 mbar and requiring that the pressure stays below 3 mbar needs pumping only 2×20 minutes per day.

The 1.4 meter large Zerodur mirrors have a thickness of 150 mm. A rather time consuming FE analysis gave the optimum radii for an 18-point axial support system implemented in the form of a whiffle-tree arrangement. The FE analysis indicated that the PV deformations of the mirror surface should be below 15 nm. The design of the whiffle-tree support system is similar to that of the Keck telescopes and is based on a number of detailed suggestions, drawings and comments from Hans Boesgaard.

3.2. Schupmann mechanics

The Schupmann corrector, shown in Figures 1B and further described in Section 4.2, consists of a fused silica lens and a Zerodur mirror. The lens is used for focusing the telescope and is mounted on a step-motor driven, high-precision vacuum compatible translation stage that ensures a variation of less than $\pm 0.003^\circ$ change in tip-tilt when used for focusing. This Schupmann focusing is controlled via RS-232 from any of the computers controlling the science CCDs. The lens is

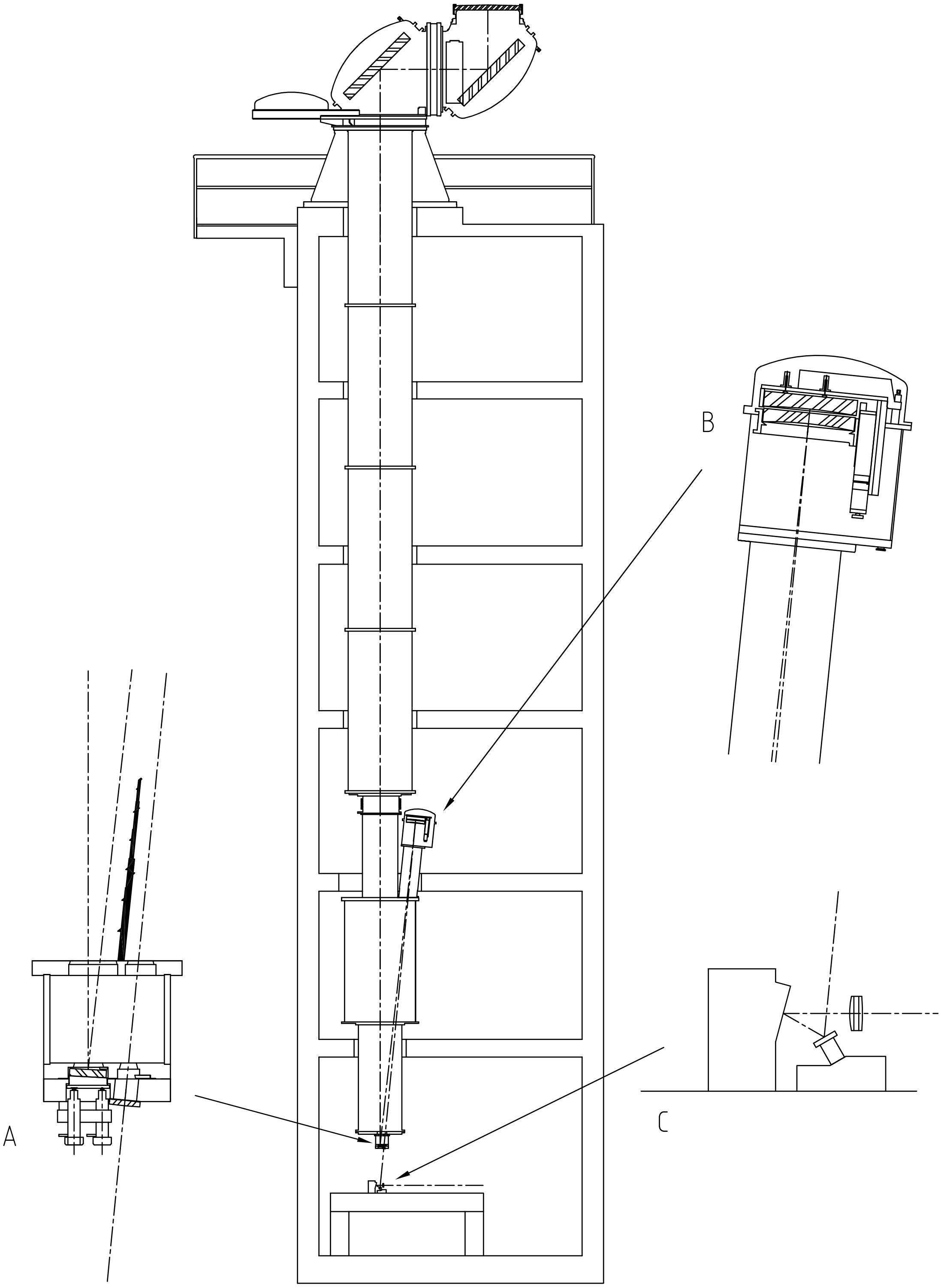

Figure 1. Schematic drawing of the tower with the turret and vacuum system (center drawing). Details of the box holding the field mirror and field lens are shown in A and the Schupman corrector with one lens and one mirror in B. The re-imaging optics, located on the optical table and consisting of a tip-tilt mirror, an adaptive mirror and a re-imaging lens are shown in C. For further details, see text.

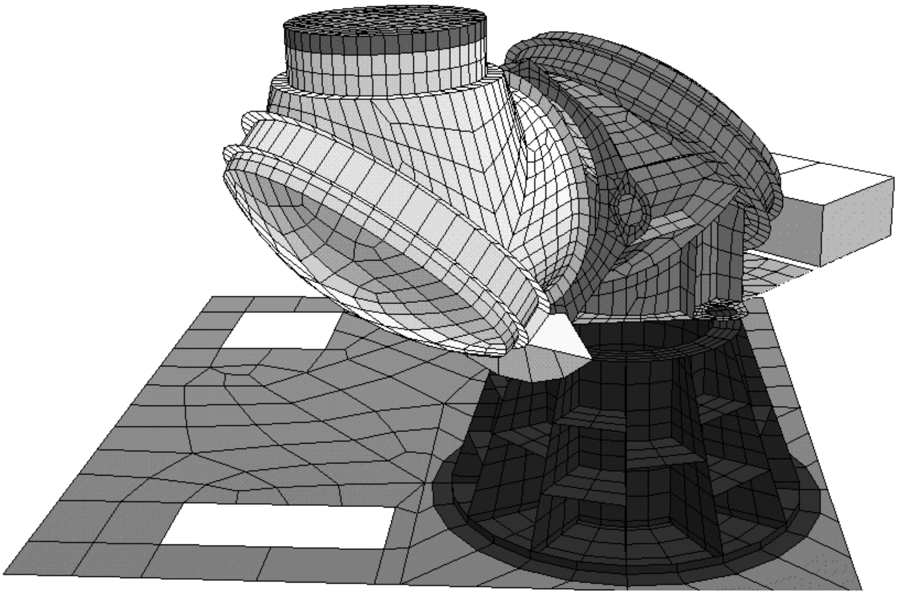

Figure 2. The Finite Element model of the telescope and tower used to determine the deflection under windload and the resonance frequency of the telescope. Not shown is the detailed model of the bearings and transmission system. The outer shell of the fundament was not included in the model but evidently added stiffness.

centered with respect to mirror and adjusted to be parallel to within ±0.01° by mechanical means only, further precision is not needed.

At the bottom of the vacuum system is located a 60 mm field mirror (see Section 4.2 for further details). The field mirror, shown shaded in the left part of Figure 1a, rests on an aluminum cylinder with a thin layer of heat-conducting vacuum grease to reduce its temperature. Tip-tilt of this mirror allows compensation of atmospheric dispersion. The cylinder is therefore pressed against an O-ring by two piezos and a small steel ball. This arrangement is free from slip-stick and allows very smooth movement of the pupil image on the Schupmann corrector and accurate compensation of atmospheric dispersion. The stroke of the piezos is equivalent to two times the stroke needed to compensate atmospheric dispersion at an elevation of 15°.

3.3. Cooling and baffling systems

Due to the relatively fast (F/21) singlet lens, given by the height of the tower, the 700 W of solar heat transmitted by the telescope is concentrated into an 18 cm diameter solar image. The heat load of 30 $\mathrm{kW/m^2}$ at the focal plane is roughly equivalent to a cooking plate and requires efficient cooling. The bottom plate of the vacuum system is made from two welded aluminium plates and have channels for water circulation covering the entire area of the plate. In addition, the top and middle plates shown in Figure 1A are designed as baffles and have cooling channels in order to minimize heating of the field mirror and field lens. All light from the singlet lens or from the Schupmann corrector that passes the middle plate hits either the field mirror or the field lens, no light can heat the lower-most plate in the box. Finally, there is a water cooled field stop at the focal plane of the Schupmann system outside the vacuum system. The liquid circulating in the cooling system is a mixture of 70% water and 30% glycol and is circulated to an outside heat exchanger. The cooling system works as intended and there are no parts external to vacuum that reach higher temperatures than 35° C, even on warm summer days.

A difficulty of the Schupmann system that must be addressed during the optical design phase is that the tilt angle between the beam from the field mirror to the Schupmann corrector and that returned to the field lens must be small in order to give good optical performance. In our design, this tilt angle is 0.7°. The design must allow a light baffle, shown in black in Figure 1A, between these two beams. This baffle must prevent illumination of the field lens by the singlet lens while not vignetting any of the beams, else unacceptable stray light will result. This baffle has small edges, barely visible in Figure 1A, carefully designed to minimize stray light from this baffle. Since the inclination of the baffle is 5° with respect to the vertical, the heat load is less than 3 kW/m^2 which is small enough that conduction plus radiation cooling is adequate to maintain an acceptable temperature. The baffle is made of copper and mounted with heat conducting grease to the upper cooling plate.

3.4. Telescope servo system

The encoder and servo system has much better potential for accurate pointing and tracking than was the case with the SVST. Based on suggestions from Torben Andersen,[2] a relatively complicated system with two current controlled motors and four encoders per axis is used. Two of the encoders are mounted directly on the motors and used as digital tachometers. The other two encoders are actually two reading heads reading the same Heidenhain ERA 880 encoder strip mounted in close proximity of the 1.2 meter gear. This encoder strip, used as position encoder, gives the potential for accurate pointing, also eliminating errors from gear irregularities, by application of pointing models. This has not been attempted yet. The servo implemented is a cascaded PI servo for both the velocity and position loops, but no systematic effort has yet been made in order to optimize the servo parameters. The computer system and software used to read the encoders and control the motors is described in Ref. 4.

A correlation tracker CCD operating at 955 Hz frame rate with a fast piezo-controlled tip-tilt mirror is used to compensate rapid image motion from seeing and any flaws in the telescope servo or gear system. The computer controlling the tip-tilt mirror calculates averages of the voltages applied to the piezos over 15 second time intervals and sends correction signals to the turret computer in order to ensure that the tip-tilt mirror operates close to its nominal tip-tilt angles. These systems allows tracking of sunspots during a whole day of observations even in bad seeing.

4. OPTICS

4.1. Primary Optical system

The primary optical system is located in the turret on top of the tower and consists of a 1.098 meter diameter, 0.97 meter clear aperture, fused silica lens and two 1.4 meter flat Zerodur mirrors. The main argument for using fused silica in the lens is its low coefficient of thermal expansion, which gives small stresses from temperature gradients. Stresses in the glass lead to birefringence which e.g. introduces spatial cross-talk from Stokes I to linear polarization. Compensating for such effects may need deconvolution. Polarimetry of small-scale structures will require accurate determination of both the ordinary wavefront errors and the spatial variation of the orientation and magnitude of the retardation across the pupil. We believe that this will be difficult if the retardation varies with the temperature gradient in the singlet objective. For example, inserting large polarizers in front of the singlet objective will change the illumination and thus temperature (gradient) of the objective, limiting the accuracy of calibrations of telescope polarization. By using fused silica instead of BK-7, this temperature sensitivity is reduced by approximately a factor 15. It should also be pointed out that birefringence leads to a reduction in the Strehl ratio which cannot be compensated by adaptive optics. We have estimated that e.g. a 2° temperature difference between the edge and the center of of a lens made of BK-7 would reduce the Strehl ratio to 0.8, thus imposing a fundamental limitation on image quality. By comparison, the birefringence from stresses in the fused silica lens is estimated to give a negligible (3%) loss of Strehl ratio.

The singlet objective has a center thickness of 82.4 mm. It has a focal length of 20.3 m at a wavelength of 460 nm, is corrected for coma and has a small aspherical correction applied to its first surface. Finite element analysis has been used to calculate the stresses and distortions of the surfaces from the vacuum load. The maximum tensile stress is 4.0 MPa which is below the recommended design stress of 6.8 MPa for fused silica. To evaluate the effects of the deformations of the surfaces of the lens, the co-ordinates of the node points were fitted to sixth-order polynomials. The corresponding coefficients are inserted in Zemax to evaluate optical performance. The analysis shows that the vacuum load adds large fourth- and sixth-order terms to both surfaces but that the resulting spherical aberration from the vacuum load is completely negligible when combining the effects of the two surfaces.

In order to minimize temperature gradients in the singlet objective, it is mounted on a short cylindrical cell, acting as cooling flange, such that the edges of the lens are exposed to air and with a shield to prevent the cell from being heated by direct sunlight. This design was used successfully with the SVST. Observations made so far show very small focus changes during the day, indicating that also spherical aberration from radial temperature gradients is small. A contributing factor to this stable behavior is probably the low UV-absorption of fused silica. Should spherical aberration be significant, we expect excellent compensation from the adaptive mirror, the design of which is made with such compensation in mind.[5]

Narrow-band imaging in e.g. H-alpha, Ca K or other important spectral lines as well as polarimetry using either filters or a spectrograph involves pass-bands of less than 0.1 nm and is possible without any chromatic correction of the singlet objective. At the bottom of the vacuum system and at the center of the optical axis, we have presently installed a flat fused silica window to allow direct imaging with the singlet. The window could be replaced by a field lens to re-image the pupil on an adaptive mirror. A final re-imaging lens would then suffice for using this mode of operation.

4.2. The Schupmann system

The Schupmann system uses a 60 mm field mirror, located 90 mm off axis at the focal plane of the singlet lens for a wavelength of 460 nm. The field mirror deflects the beam upwards and away from the optical axis of the telescope. This beam is maintained within the vacuum system because it is comparatively long, 5.3 meters, and because it re-images the one-meter singlet objective on a 25 cm large corrector. This corrector consists of a negative lens and a mirror. The effect of the lens, when used in double pass, is to effectively cancel out the 1-meter fused silica lens, the effect of the mirror is to create a perfectly achromatic image at the secondary focus. This concept was proposed by Ludwig Schupmann 100 years ago.

The idea of using a singlet lens in combination with a Schupmann corrector for solar telescopes has been proposed earlier by Refs. 6, 7 and also by Dunn as an early concept for LEST.[8] It was later considered for the Pic du Midi refractor,[9] but was rejected because of strong off-axis aberrations. The Schupmann design has been implemented on several telescopes during the last 40 years with mixed results. Of these can be mentioned the two coronagraphs at Climax and at the Sacramento Peak observatories, both of which had serious optical problems. These designs used correctors with a single component, consisting of a meniscus lens silvered on its backside. For solar telescopes, a corrector consisting of a meniscus lens followed by a Zerodur mirror appears a better choice which also adds one more degree of freedom in the optimization. Also, in the present design, the Schupmann corrector with its field mirror is mounted at fixed orientation in the relatively stable environment inside the tower. Nevertheless, these earlier failures in implementing functioning Schupmann systems prompted a thorough tolerance analysis which was carried out by one of us (B.L.) using Zemax. This analysis involved investigation of the effects of large temperature variations in the singlet lens, Schupmann corrector lens and outside air temperature as well as tolerances on curvatures, de-centering, tip-tilt and translation along the axis of the Schupmann corrector lens relative to the mirror. The conclusion was that no particular problems are expected. A 0.02° tilt of the Schupmann corrector lens introduces approximately 1/40 wave of coma which increases linearly with the tilt angle. Ensuring tilt angles smaller than that is straightforward by mechanical means, because of the small separation between the Schupmann corrector lens and mirror. Furthermore, considerably larger coma would be correctable with the adaptive mirror. Translation of the corrector lens along the optical axis gave rise to approximately 20 times larger shift of the Schupmann focal plane but with no significant other aberrations appearing. It was concluded that movement of this lens was ideal for focusing the telescope and this was implemented in the design.

In order to give diffraction-limited image quality, either the corrector lens or the mirror needs approximately six waves PV correction for spherical aberration. The excellent performance of the telescope after correction by the Schupmann system is shown in Table 1. The design was optimized using Zemax with tilt-angles for the field mirror and the Schupmann mirror to allow installation of baffles to reduce stray-light. Early designs showed excellent NIR performance but poorer performance at short wavelengths. By adjusting the curvatures of the singlet objective such that its focal plane agrees with the location of the field mirror at 460 nm, a better balance between NIR and blue performance is obtained. The present design allows diffraction limited performance (Strehl ratio 0.8 or higher) over the whole 330–1100 nm wavelength range at a single focus position.

The Schupmann system is a symmetric 1:1 re-imaging system and is free from coma, provided that the tilt angle of the lens relative to the mirror is kept within tolerances. However, the tilt angle between the beam from the field mirror to the Schupmann corrector and the beam returned to the field lens introduces astigmatism. Earlier design studies of Schupmann systems have shown that this astigmatism can be compensated by tilting the singlet lens and our design studies confirm this. In the present design, tilt of the singlet is introduced by locating the field mirror off-axis by approximately 0.25°, corresponding to 90 mm in the focal plane. In the design optimization, the tilt angle between the beams to and from the Schupmann corrector was kept at a fixed angle of 0.7° and the distance from the optical axis of the singlet to field mirror was optimized by Zemax. The optimization also took advantage of the extra degree of freedom obtained by using a corrector consisting of a separate lens and mirror. Analysis of the design showed that Zemax minimized astigmatism in the

Table 1. The table below shows calculated RMS spot diameter, Airy diameter, RMS wave aberration, and Strehl ratio for the final design. All values are for a single focal plane, which is the best compromise for the wavelength range 350 nm–1100 nm. All wavelength have equal weights. The image quality values varies slightly over the focal plane. The values in the table are for the worst points. The units for the spot diameters is microns, and for the wave aberration it is wavelengths.

Wavelength	RMS spot diameter	Airy diameter	Wave aberr. RMS	Strehl ratio
350–1100	7			
350–650	5.6			
650–1100	7.6			
330*	10	16.8	0.07	0.82
350	9	17.8	0.06	0.87
400	5	20.3	0.03	0.97
550	4	28	0.02	0.98
800	7	41	0.026	0.97
1100	10	56	0.028	0.97

* The center point of the field. The difference from the worst point is small.

Schupmann system by making the second surface of the corrector lens nearly flat. The analysis also showed that making that surface perfectly flat had negligible impact on the performance while simplifying polishing and testing.

From the tolerance analysis, the image of the singlet needs to be accurately centered on the corrector in order to not give rise to dispersion. Displacing the pupil image of the singlet by tilting the field mirror, causes dispersion in the image plane. The amount of dispersion corresponds to 160 micron, or 1.7 arcsec, separation between the 400 and 900 nm wavelengths per mm decenter. An important feature of the Schupmann system is its ability to compensate atmospheric dispersion. Table 2 shows the atmospheric dispersion at 15° elevation for an altitude of 2400 m as calculated for wavelengths in the range 350–1100 nm. Also shown is the residual dispersion after optimum compensation with the Schupmann system. The Schupmann corrector allows the effects of atmospheric dispersion to be reduced by approximately a factor 15–50, depending on the chosen wavelength interval. The compensation is excellent (improvement factor greater than 50) over the visible–UV part of the spectrum and still very good at NIR wavelengths.

The Schupmann design allows an un-obscured pupil and perfect chromatic correction by using an off-axis system and is as a result of this limited to good correction over a fairly limited field. Ray-trace calculations indicate diffraction limited performance over an approximately 3 arcmin field. The diameter of the field mirror is 60 mm, or approximately one third of the solar diameter. This mirror has a rectangular baffle of 40 × 44 mm that can be opened to 44 × 44 mm in order to increase the un-vignetted field of view at near infrared wavelengths. The small field mirror with its baffle reduces the heat load on the Schupmann corrector and should also lead to reduction of stray-light while giving an un-vignetted field of view of 3 arcmin at most observable wavelengths. By locating the field mirror at the focal plane of the singlet at 460 nm, there will be vignetting of part of the field at the longest wavelengths, but this has been considered an acceptable trade-off in order to enhance the performance at blue wavelengths.

Neither the primary optical system nor the Schupmann system has any plane-parallel surfaces that can introduce fringes.

Table 2. Atmospheric dispersion at 15° elevation, before and after correction by field mirror tilt.

Wavelength range	Atmospheric dispersion	Residual dispersion	Pupil movement	Improvement factor
350–1100 nm	680 μm (7″)	45 μm (0.46″)	3 mm	15
400–900 nm	480 μm (5″)	20 μm (0.2″)	3 mm	24
350–650 nm	540 μm (5.6″)	$<$ 10 μm (0.1″)	3.2 mm	$>$ 55
700–1100 nm	110 μm (1.1″)	11 μm (0.11″)	2.3 mm	10

The Schupmann design, by requiring a large singlet lens, is of no interest for future very large solar telescopes but is an attractive concept for an evacuated meter-class solar telescope with adaptive optics. The mirror in the Schupmann corrector can be replaced with a curved adaptive mirror, reducing the number of optical surfaces. Early design studies indicate the feasibility of 1.2-m F/33 telescope with much smaller diameter for the Schupmann corrector.[10]

5. OPTICAL QUALITY AND TESTING

It is sometimes argued that telescopes equipped with adaptive optics require only low optical quality. We believe that this is not correct. Adaptive optics systems use wavefront sensors which have a limited spatial resolution at the pupil. Telescope aberrations at spatial frequencies higher than resolved by the wavefront sensor will, because of aliasing, be interpreted as low-order aberrations by the wavefront sensor. An adaptive optics system operating in closed loop will thus introduce fixed low-order aberrations in addition to the high-order aberrations which cannot be corrected by the adaptive mirror.

In order not to be forced to use a high-order adaptive optics system and in order that the accumulated aberrations of the telescope, secondary optical system, adaptive mirror and any subsequent re-imaging optics shall be negligibly small compared to those of the atmosphere in very good seeing, consistent high optical quality is needed. The specifications for the two turret mirrors were 20 nm surface quality PV over any sub-aperture with 300 mm diameter and 50 nm PV over the entire surface. The required optical quality for the singlet objective was similar. In order to achieve such high quality for the singlet lens, high homogeneity in the refractive index is needed. The fused silica blank manufactured by Corning has refractive index variations within $\pm 1.5 \times 10^{-6}$. These variations are not small enough to ensure the targeted wavefront quality and local polishing was required. To ensure the feasibility of local polishing, limits for the maximum gradients in refractive index were added to the specifications of the blank. Apart from a small anomaly at the center, having approximately 70 mm diameter, local polishing was successful in achieving the required wavefront quality.

It should be noted also, that for large Zerodur mirrors heated by sunlight, axial temperature gradients will result and that even small axial CTE gradients may cause serious distortions of the mirror surface. The measured CTE variations in samples taken from the same boule as used to produce the Zerodur blanks indicate very high homogeneity.

The optics was polished by Opteon Oy and tested by one of us (TK) in Finland. The main challenge in polishing optics of these dimensions to the above specifications is in the optical testing. During polishing, low frequency deviations from flatness for the flat turret mirrors was tested with the pentaprism method.[11] Later, high-frequency errors were tested with the interferometric Hartmann method[12] using the lens as collimator (see below).

The 1-meter singlet lens was polished in a heated lab and needed several days of temperature stabilization in the much cooler test tunnel before optical tests could be made. This lens was tested in auto-collimation using one of the 1.4 meter Zerodur mirrors. In order to eliminate effects from any imperfections in the test mirror and stratification effects in the tunnel, the lens was rotated through 8 angles and the so-obtained wavefronts were rotated and co-added. During these tests, the interferometric Hartmann method[12] was used. Final tests demonstrated a wavefront quality of 9.9 nm RMS, after removing a few low-order Zernike aberrations. Removing low-order Zernike aberrations was justified since these will be easily compensated by the adaptive optics system. By similarly rotating the Zerodur mirror, verification of its quality over the center 1-m diameter could be obtained. The quality in the reflected wavefront from the mirrors was approximately 12 nm RMS, again after removing a few low-order aberrations. When used at 45° angle of incidence, these wavefront errors are divided by $\sqrt{2}$, or approximately 8–9 nm RMS. It is concluded that the optical quality of the main optics is excellent with respect to high-frequency errors that are uncorrectable with the adaptive optics system.

The Schupmann corrector mirror and lens uses oversized blanks, 300 respectively 305 mm diameter for a pupil diameter slightly larger than 250 mm and a highly homogeneous fused silica blank. The final wavefront RMS of the entire corrector (lens plus mirror) was 8.3 nm RMS, after removing a few low-order aberrations.

6. ADAPTIVE OPTICS

The adaptive optics system is described in more detail separately in these proceedings.[5]

The goal of the 1-m telescope is diffraction limited imaging and near-diffraction limited spectroscopy and polarimetry in excellent seeing, corresponding to $r_0 > 20$ cm. Measurements made during the LEST site testing campaign,[13] as well as experience with the SVST, indicate that such seeing conditions should occur 5% of the time. Simulations indicate that near diffraction-limited imaging, corresponding a wavefront RMS of less than $\lambda/10$, should be achievable under such conditions with an AO system correcting the first 10 Karhunen–Loève or Zernike modes. In order to allow for a 50% efficiency of the AO system, at least 20 modes need to be corrected.

We feel confident that a low-order adaptive optics system can efficiently compensate seeing in good–excellent seeing conditions ($r_0 > 12$ cm) but also that operation of high-order AO systems to correct poorer seeing is considerably more difficult and may have problems to provide high Strehl ratio in excellent seeing.

We are presently developing an adaptive optics system based on a 37 electrode bimorph mirror from AOPTIX Technologies Inc.[14] This mirror is capable of correcting approximately 30–35 Karhunen–Loève modes. Recent improvements in the manufacturing process should allow this mirror to be flattened to within 1/10 wave PV.

The optical arrangement is shown in Fig. 1A and 1C. The field lens, shown in the right-hand lower part of Fig. 1A, is used as exit vacuum window and puts a 34 mm pupil diameter on the adaptive mirror via reflection on the 40-mm tip-tilt mirror (Fig. 1C). The angle of incidence is 30° on the tip-tilt mirror and 15° on the adaptive mirror in order to give a nearly circular pupil image. Following these mirrors is a apochromatic triplet that provides a final image scale of about 0.04 arcsec on the science CCDs.

The wavefront sensor for these adaptive optics systems is a 37-element hexagonal Shack–Hartmann wavefront sensor, matched to the geometry of the adaptive mirror.

The 1-meter solar telescope has already been used with a 19-electrode adaptive optics system, developed for the SVST. This system has already given long time sequences of near-diffraction limited images at 430 nm wavelength with the new telescope, thus validating the ability of a low-order adaptive optics system to reach 0.1 arcsec resolution.

7. INSTRUMENTATION

The main instruments for the NSST will be the following: imaging CCDs, including three 2000 × 2000 Kodak CCDs, an H-alpha filter and a short Littrow spectrograph. The Littrow spectrograph is designed for simultaneous observations in up to three wavelengths and will have a replaceable focal plane and slit unit to allow spectro-polarimetry. The spectrograph is optimized for high spatial resolution but modest spectral resolution and is expected to be operational in the middle of 2003.

In addition, we will use broad-band G-band and Ca K filters.

The telescope will also have a tunable narrow-band filter for imaging, Doppler measurements and polarimetry. It is not yet completely clear whether Lockheed's SOUP filter will be placed on La Palma. Plans are also for a Michelson Solar Polarimeter (MSP, designed by Lockheed–Martin). The MSP system uses a Michelson–Lyot filter, would allow 0.14 arcsecond resolution and obtain high signal-to-noise, vector magnetograms of the solar photosphere over a 85 arcsecond field-of-view on a 10 second cadence.

It is expected that further instrumentation will be added on a permanent or semi-permanent basis through partnerships with other institutes. Also, co-observing with the Dutch Open Telescope (DOT), which is controlled from the same building as the new telescope, will enhance the scientific outputs from both telescopes.

8. CONCLUSIONS

The 1-meter Swedish solar telescope has an optical design that is different from that of all other major solar telescopes. It is based on a simple primary optical system with a corrector to compensate chromatic aberrations (longitudinal color and atmospheric dispersion) and a flexible and accessible re-imaging system with adaptive optics on the optical table in the observing room. This telescope is the largest in Europe, the second in the World and is the first telescope to reach a spatial resolution of 0.1 arcsecond. The telescope still needs additional instrumentation to fully exploit its scientific potential, but is otherwise a fully functioning scientific instrument. For first results obtained with this telescope, see Refs. 15, 16.

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