

First Results from the Swedish 1-m Solar Telescope

Göran B. Scharmer, Dan Kiselman, Mats G. Löfdahl & Luc H. M. Rouppe van der Voort

Institute for Solar Physics of the Royal Swedish Academy of Sciences, AlbaNova University Center, SE-106 91 Stockholm, Sweden

Abstract. We describe the Swedish 1-m Solar Telescope (SST) on La Palma which has twice as large aperture as the previous SVST. The un-obscured optics consists of a singlet lens used as vacuum window and secondary optics. The secondary optics uses a field mirror to re-image the pupil on a 25 cm corrector which provides a perfectly achromatic image, compensated also for atmospheric dispersion. The adaptive optics system 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 on 21 May 2002 and has quickly proven to be the most highly resolving solar telescope ever built. In this paper, we describe its design, the instrumentation in use or planned for this telescope and present first results based on observations made in May–July 2002.

1. Introduction

The priority of the Swedish 1-m Solar Telescope (SST) was its scientific usefulness, a simple and straightforward design and a short time to deployment. This was implemented in the form of an evacuated telescope similar in its design to the SVST. In this paper, we briefly describe this design, referring to Scharmer et al. (2002a) for more details, and demonstrate examples of near diffraction-limited images. Section 2. describes the mechanical design, Sect. 3. the optical design and Sect. 4. the adaptive optics system. Section 6., finally, discusses the results of the first observations and Sect. 7. adds some concluding remarks.

2. Mechanical design

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.

2.1. 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

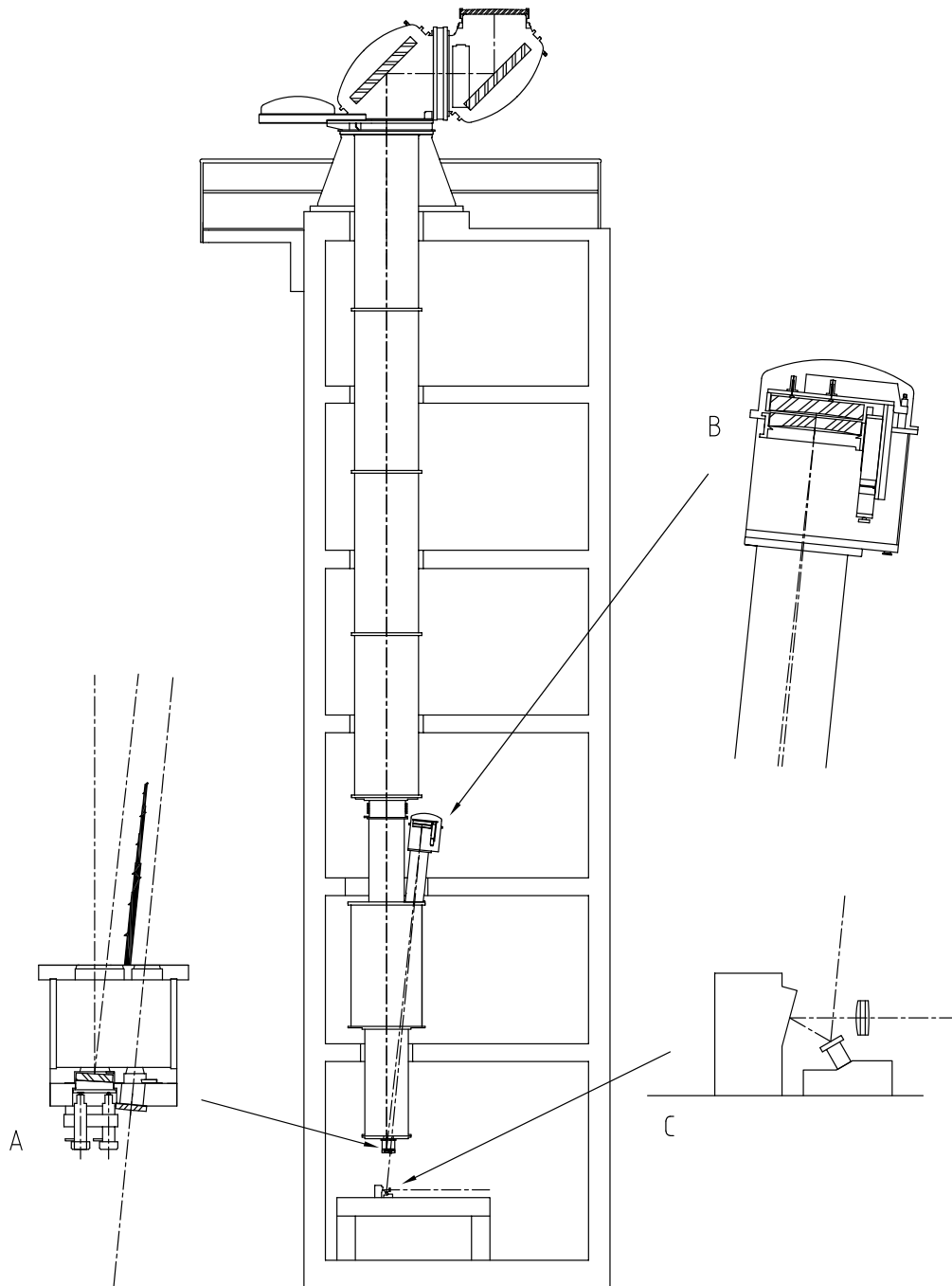


Figure 1. Schematic drawing of the tower with the turret and vacuum system (center drawing). Details of the box holding the field mirror and field lens are shown in A and the Schupman corrector with one lens and one mirror in B. The re-imaging optics, located on the optical table and consisting of a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

operate with relatively high bandwidth. In order to ensure a stiff design, a finite element model of the telescope and the roof of the tower was made, based on a preliminary design. Re-design of the gear system increased the first resonance frequency to 12–15 Hz, as measured with the telescope on the tower, and reduced deflections from wind-load to less than 1'' with 15 m/s winds.

Another critical part of the design was the 1.1 meter large rotating vacuum seals. Repeated discussions with the manufacturer 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. 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 min per day.

2.2. 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 kW/m² at the focal plane is roughly equivalent to a cooking plate and requires an efficient water cooling system. Such a system has been installed and works as intended.

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.

3. Optics

3.1. Primary Optical system

The primary optical system is located in the turret on top of the tower and consists of a 1.098-m diameter, 0.97-m clear aperture, fused silica lens and two 1.4-m 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 gradient, thus allowing stable polarization properties.

The singlet objective 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. 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. 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 (Scharmer et al. 2002b).

3.2. The Schupmann system

The Schupmann corrector, shown in Figure 1B, consists of a fused silica lens and a Zerodur mirror that is fed by light from a 60-mm field mirror (see Figure 1A) located 90 mm off axis at the focal plane of the singlet lens. This beam is maintained within the vacuum system because it is comparatively long, 5.3 ms, and because it re-images the 1-m singlet objective on a 25-cm large corrector. The 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-m fused silica lens, the effect of the mirror is to create a perfectly achromatic image at the secondary focus. Translation of the corrector lens along its optical axis is used for focusing the telescope.

The Schupmann design was optimized with fixed tilt-angles for the field mirror and the Schupmann mirror to allow installation of baffles to reduce stray-light. The tilt angle between the beam from the field mirror to the Schupmann corrector and the beam returned to the field lens introduces astigmatism which can be compensated by tilting the singlet lens. Such tilt of the singlet is introduced by locating the field mirror off-axis by approximately $0^{\circ}25$, corresponding to 90 mm in the focal plane. The corrector lens has approximately six waves PV correction for spherical aberration. The final design allows excellent performance (Strehl ratio 0.9 or higher) over the whole 360–1100 nm wavelength range at a single focus position and slightly lower Strehl ratio (0.82) at 330 nm.

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 $160 \mu\text{m}$, or $1''7$, 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. 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 (350–650 nm) and still very good (improvement factor 24) at visible–NIR wavelengths (400–900 nm).

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 and the fast (F/21) singlet lens limited to good correction over a fairly limited field. Ray-trace calculations indicate diffraction-limited performance over an approximately $3'$ field. 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 $3'$ at most observable wavelengths.

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

4. Adaptive Optics

The adaptive optics system is described in more detail separately by Scharmer et al. (2002b).

The goal of the SST is diffraction-limited imaging and near-diffraction limited spectroscopy and polarimetry in excellent seeing, corresponding to $r_0 > 20$ cm. 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.

The SST has so far 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 $0''.1$ resolution. We are presently developing an adaptive optics system based on a 37-electrode bimorph mirror from AOptix (2002). This mirror is capable of correcting approximately 30–35 Karhunen–Loève modes. A notable feature of this and the previous AO system is that the adaptive mirror can be flattened to within $1/10$ wave PV by using the Shack–Hartmann wavefront sensor (below), without the need for an additional interferometer.

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 an apochromatic triplet that provides a final image scale of about $0''.04$ on the science CCDs.

The wavefront sensor for this adaptive optics system is a 37-element hexagonal Shack–Hartmann wavefront sensor, matched to the geometry of the adaptive mirror. A DALSA CCD, operating at a frame rate of 955 Hz, is interfaced to a dual processor PC, operating under Linux, that also controls the electrode voltages of the adaptive mirror.

4.1. Correlation tracker and tip-tilt mirror

A decision was taken not to use the bimorph mirror also for tip–tilt control, although bimorphs normally allow excellent tip–tilt correction if used with small amplitude. The reason for this decision was partly to avoid using the bimorph mirror at 45° angle of incidence which would require a larger mirror diameter that would have lower resonance frequency. Another reason was that we had not yet proven that the telescope tracking system was good enough to require only small-amplitude tip–tilt correction, since bimorphs introduce significant high–order aberrations when used for tip–tilt correction at large amplitude. Finally, a separate CCD with large field of view for correlation tracking offers more robust performance than a system that uses fewer pixels. Should there be reasons, it will be possible to eliminate the tip–tilt mirror and replace the bimorph mirror later.

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 s 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.

5. Instrumentation

The main instruments for the NSST will be the following: imaging CCDs, including three 2000×2000 Kodak CCDs, an H- α 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.

We are presently designing a rotating holder for a linear polarizer to be mounted in front of the 1 m singlet lens, such that the polarization properties of the telescope can be modeled and corrected for.

The telescope will also have a tunable narrow-band filter for imaging, Doppler measurements and polarimetry. It is not yet completely clear when Lockheed's SOUP filter will be placed on La Palma. Plans are also for a Michelson Solar Polarimeter (MSP). The MSP system uses a Michelson-Lyot filter, would allow $0''.14$ resolution and obtain high signal-to-noise, vector magnetograms of the solar photosphere over a $85''$ field-of-view with a cadence of 10 s. In addition, we will use G-band and Ca K filters.

It is expected that further instrumentation will be added on a permanent or semi-permanent basis through existing or future partnerships.

6. First observations and results

The SST achieved first light on 2 March 2002, but then without adaptive optics or Schupmann system and stopped down to 60 cm. Imaging through narrow Ca II K and H- α filters demonstrated that the telescope system and primary optics worked without any apparent flaws. Following this, the Schupmann corrector was successfully installed 5 April, so that the first scientific observations (aperture still stopped down) could take place during the last week of April for a programme to observe umbral flashes (Rouppe van der Voort et al. 2003). After the 19-electrode AO system and the cooling was installed, the telescope was opened to full aperture on 21 May. Already the next day, diffraction-limited images, achieving $0''.11$ – $0''.12$ resolution with the 1-m aperture, were acquired. These showed new features in and around sunspots which, together with the results of follow-up observations during June and July, were presented by Scharmer et al. (2002c) and Löfdahl & Scharmer (2002).

The major result of the discovery published in Nature was that many bright penumbral filaments show dark cores within them – at least when seen at the center of the disk. Examples of this can be seen in Fig. 2 and in Figs. 3(a) and (b). These cores are unresolved so that their true widths must be less than 90 km. The cause of these dark cores remains unexplained. The collage of G-band pictures in Fig. 3 are from July 15 (a,b), showing dark cores in penumbral filaments and faint double-structured filaments, called "ghosts" in the umbra, May 22 and June 2 (c,d) showing double structure and other peculiar granular

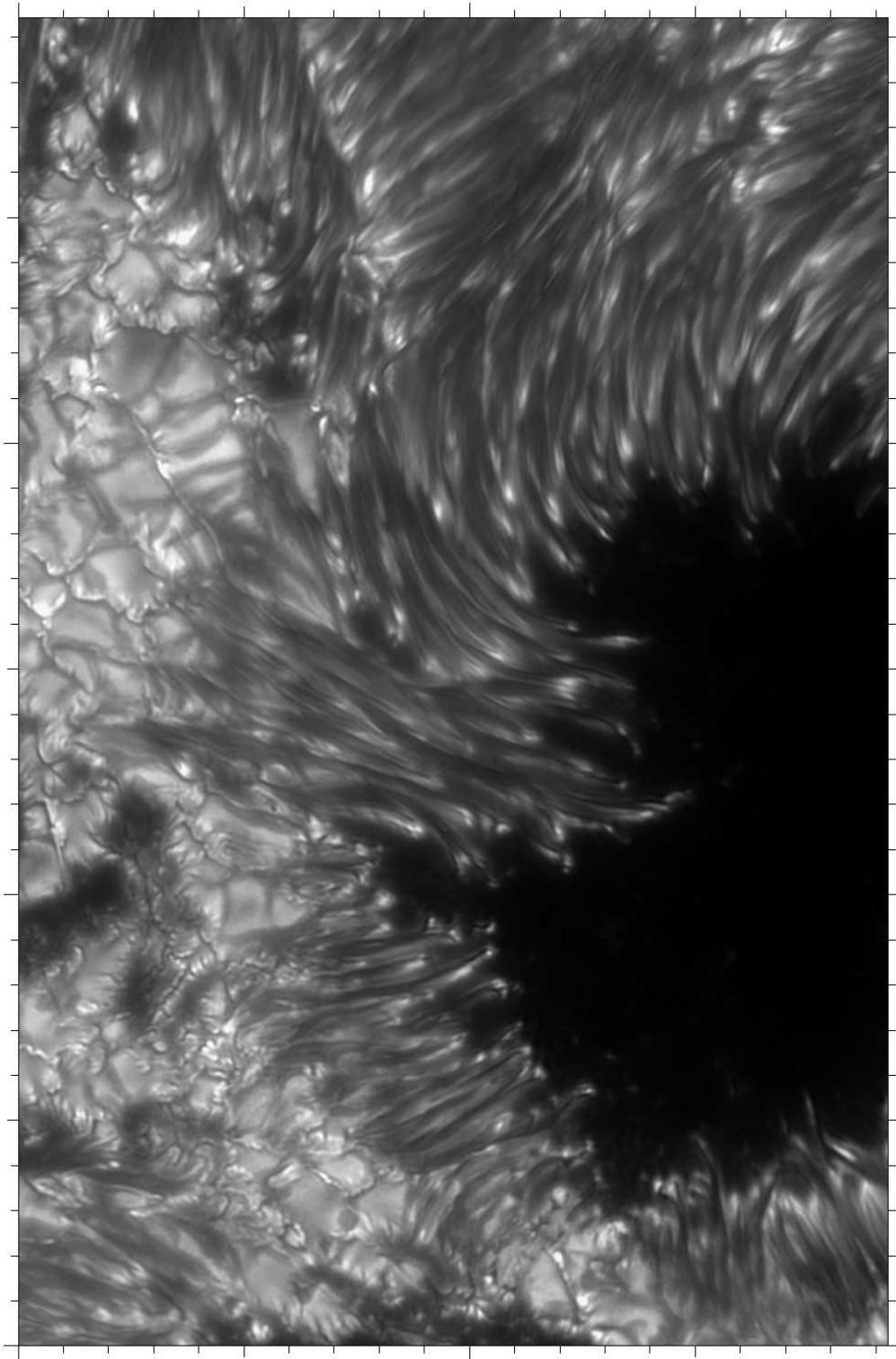


Figure 2. Part of AR10030, 15 July 2002, (see Scharmer et al. 2002c).

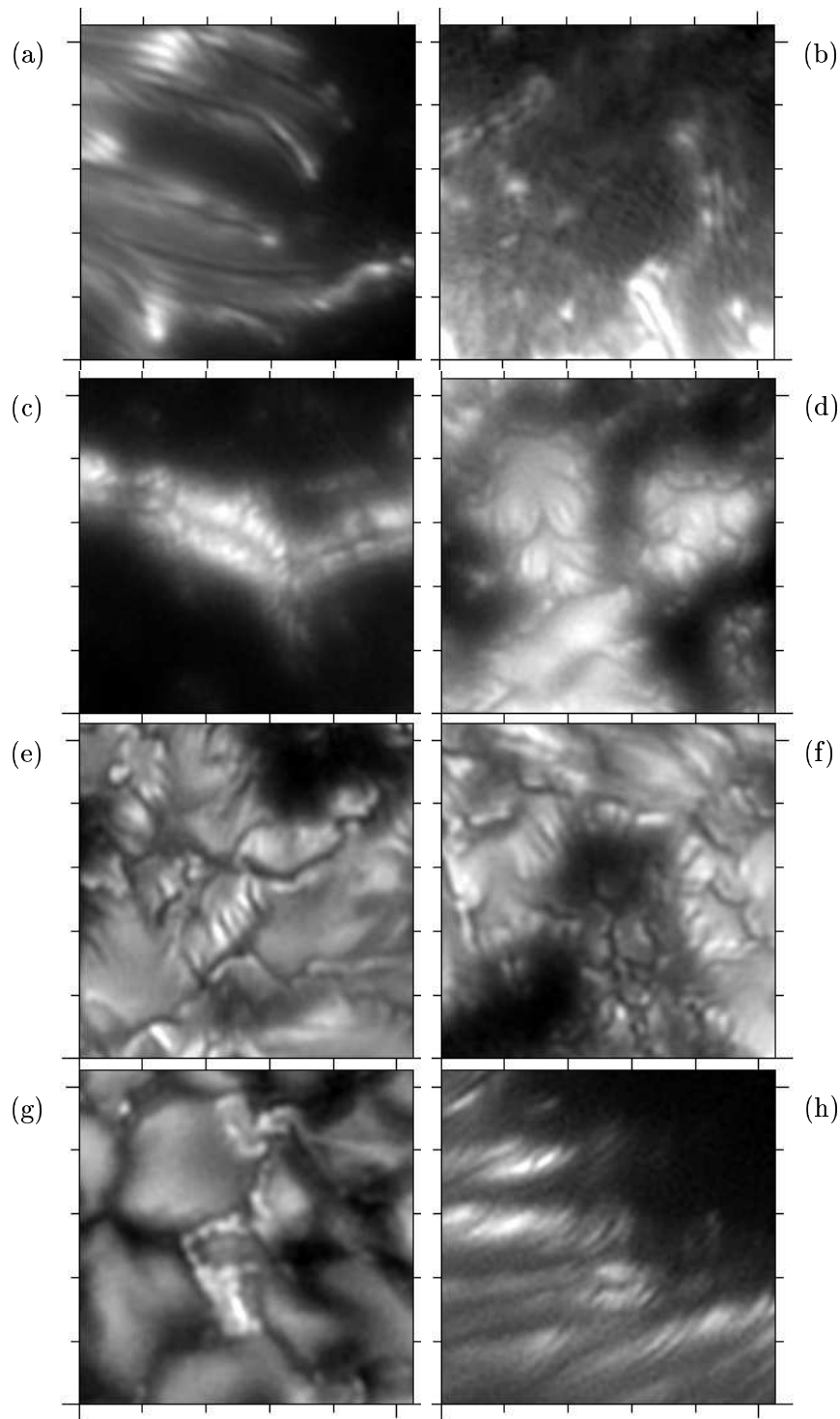


Figure 3. Sample fine structure. (a) Dark cores, (b) ghosts, (c) light bridge dots, (d) light bridge granules, (e) canals, (f) hairs, (g) bright points, (h) streaks. See text for description. 1'' tick marks.

structure in light bridges, July 15 (e,f) showing narrow streaks and "canals" in granulation near pores, May 22 (g), showing tiny bright points and finally from June 11 (h) showing streaks in penumbral filaments observed off disk center at $\mu = 0.72$.

The data of Scharmer et al. (2002c) are being made public through our web pages: <http://www.solarphysics.kva.se>. They consist of images and movies of sunspots, notable is a sequence of 1 h 20 min from 15 July. We will continue to make data public in this manner and hope that the community will make good use of it.

7. Conclusions

The SST, by using a singlet lens as vacuum window and an in-vacuum Schupmann corrector, has an optical design that is different from that of any previous solar telescope. This telescope is the largest in Europe, the second in the world and is the first solar telescope to reach a spatial resolution of $0''.1$. The telescope still needs additional instrumentation to fully exploit its scientific potential, but is otherwise a fully functioning and powerful scientific instrument.

Acknowledgments. Construction of the SST was funded by the following private foundations in Sweden: Knut och Alice Wallenbergs Stiftelse, Marianne och Marcus Wallenbergs Stiftelse, Stiftelsen Marcus och Amalia Wallenbergs Minnesfond and the Royal Swedish Academy of Sciences. Important contributions to construction costs, operating costs and instrumentation have been made by the Oslo University and Lockheed–Martin Solar and Astrophysics Lab. The Swedish 1-m Solar Telescope is operated by the Royal Swedish Academy of Sciences within the Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias on the island of La Palma, Spain.

A large number of individuals and companies contributed to the design or construction of this telescope, of these the following should be mentioned in particular: Bertil Petterson and Klas Bjelksjö made all the design drawings of the telescope, oversaw the manufacturing of all parts and also made the test- and final assemblies of the telescope in Gothenburg and on La Palma. We also want to express special gratitude to Svenska Bearing AB, who manufactured all large parts of the telescope with dedication, precision and remarkable speed. Peter Dettori re-wrote the entire AO-code and ported it to operate on a PC under Linux. His crucial contribution is gratefully acknowledged.

References

- AOptix Technologies, Inc. 2002, (formerly Laplacian Optics Inc.), 580 Division Street, Campbell, CA 95008, USA, <http://www.aoptix.com>
- Löfdahl, M. G. & Scharmer, G. B. 2002, in Proc. SPIE, Vol. 4853-54, Innovative Telescopes and Instrumentation for Solar Astrophysics, ed. S. Keil & S. Avakyan, in press
- Roupe van der Voort, L. H. M., Rutten, R. J., Sütterlin, P., Sloover, P. J., & Krijger, J. M. 2003, A&A, submitted

- Scharmer, G. B., Bjelksjö, K., Korhonen, T. K., Lindberg, B., & Pettersson, B. 2002a, in Proc. SPIE, Vol. 4853-47, Innovative Telescopes and Instrumentation for Solar Astrophysics, ed. S. Keil & S. Avakyan, in press
- Scharmer, G. B., Dettori, P., Löfdahl, M. G., & Shand, M. 2002b, in Proc. SPIE, Vol. 4853-52, Innovative Telescopes and Instrumentation for Solar Astrophysics, ed. S. Keil & S. Avakyan, in press
- Scharmer, G. B., Gudiksen, B. V., Kiselman, D., Löfdahl, M. G., & Rouppe van der Voort, L. H. M. 2002c, *Nature*, 420, 151