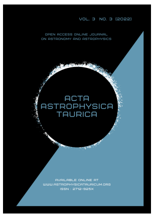
Open Access Online Journal on Astronomy and Astrophysics
Acta Astrophysica Taurica
www.astrophysicataauricum.org



Acta Astrophys. Tau. 3(3), 8–11 (2022)
doi:10.34898/aat.vol3.iss3.pp8-11

Experiments on high-spatial-resolution observations of the Sun at the A.B. Severny Solar Tower Telescope of the Crimean Astrophysical Observatory

A.S. Kutsenko[1], Shangbin Yang[2,3], V.I. Abramenko[1], D.G. Semyonov[1]

[1] Solar Physics Laboratory, Crimean Astrophysical Observatory, Nauchny, Crimea, 298409, Russia
e-mail: `alex.s.kutsenko@gmail.com`
[2] Key Laboratory of Solar Activity, National Astronomical Observatories of China, Beijing, 100101, China

[3] University of Chinese Academy of Sciences, Beijing, 100049, China

Received 26 November 2021

ABSTRACT

In this paper, we describe high-cadence and high-spatial-resolution observations of the Sun acquired by the A.B. Severny Solar Tower Telescope (STT-1) in October and November, 2021. The spatial resolution of ground-based optical telescopes is usually limited by seeing. However, the spatial resolution can be improved significantly by a post-processing of hundreds of short-exposure images of the object. In order to get the data required for the post-processing, the telescope was equipped with a camera and a high-speed detector. The detector was able to take up to tens of frames per second, which is necessary for speckle-reconstruction of the solar surface images. A thorough visual analysis of the reconstructed images as well as their comparison with the data provided by SDO/HMI yielded very promising results. Individual granules as well as penumbral fibrils are clearly seen in the images. High-spatial-resolution observations by STT-1 provide new opportunities for the studies of the Sun.

Key words: Sun, sunspots, granulation, instrumentation

1 Introduction

Over the past decades, the studies of the Sun have been headed toward the analysis of the structure and dynamics of small-scale features: the granulation in the quiet-Sun regions, small magnetic elements, penumbral fibrils of sunspots, the Ellerman bombs, etc. This tendency can be explained by the fact that non-stationary processes in solar quiet and active regions occur within small spatial scales of an order of tens of kilometers.

Such studies have become possible due to construction of new instruments with unprecedented capabilities. A number of large solar telescopes are under construction or have already started their scientific programs. We can mention the largest Daniel K. Inouye Solar Telescope (DKIST, Rimmele et al., 2020) so far with a 4 m primary mirror (USA), the 1.6 m clear aperture Goode Solar Telescope (GST, Goode et al., 2010) at the Big Bear Solar Observatory (BBSO, USA), the 1 m New Vacuum Solar Telescope (NVST, Liu et al., 2014) at the Yunnan Observatories (PRC), a number of European solar telescopes at the Canary Islands. Large solar telescopes are being built in India, China, and Europe. The Institute for Solar-Terrestrial Research in Russia is building a solar telescope with a 3 m primary mirror.

The best spatial resolution of a telescope is determined by the diffraction limit (the Rayleigh criterion):

$$\alpha = 1.22\lambda/D, \tag{1}$$

where λ is the wavelength, D is the diameter of the primary mirror. Thus, at $\lambda = 500$ nm and $D = 1.6$ m the maximal resolution of the telescope is $\alpha \approx 0.08''$. However, in practice the real resolution is limited by seeing: the wavefront of the incident light is distorted by the turbulence in the atmospheric layers. The theory of wavefront distortion was developed by Fried (1966). The "quality" of the seeing is evaluated using the Fried parameter. The seeing-limited resolution may achieve $0.5''$ under the best conditions.

To overcome the limitations introduced by seeing, adaptive optics is often used in modern instruments. The wavefront sensors in such systems measure the distortion of the wavefront. This information is used to correct the surface of one or several mirrors in order to compensate for atmospheric distortions. The construction and implementation of adaptive optics are extremely difficult and expensive tasks. Besides, the operation of the adaptive optics is only possible under appropriate seeing when the wavefront can be corrected in principle. Mathematical approaches are usually applied to further improve the spatial resolution of the acquired images. All these techniques allow one to obtain diffraction limited observations and to achieve the spatial resolution of an order of a hundredth part of arcsec (or several tens of kilometers at the solar surface).

The A.B. Severny Solar Tower Telescope (STT-1) is a Nasmyth 90 cm primary mirror telescope. Using Equation (1) we can easily estimate the diffraction limit of the telescope to be $\alpha \approx 0.14''$ at $\lambda = 500$ nm wavelength. According to model simulations, due to an off-axis optical scheme, optical aberrations decrease the theoretical resolution of the telescope down to $0.3''$ (V. Terebizh, 2021, private communication). Nevertheless, even this value is sufficiently lower than the limit determined by the seeing: the spatial resolution is of about 1.5–2$''$ during daytime observations (Gaze, 1948).

Mathematical approaches aimed at spatial resolution enhancement might be applied to the observations of any telescope. These approaches will succeed if two conditions are satisfied: i) the atmospheric seeing is good enough to get contrast details in the acquired images and ii) the exposure of a single frame does not exceed several milliseconds. The latter requirement is determined by the characteristic time of atmospheric turbulence, which is of an order of 10–20 ms (e.g., von der Luehe, 1984). If the exposure is considerably shorter than this value, one can assume the atmosphere to be “frozen”. The image of the object can be reconstructed using hundreds of short-exposure frames. Note that the object itself has to remain unchanged during the entire interval of observations. A software for the post-processing is well-developed even for amateur astronomers.

Our aim in this work is to figure out whether we can use STT-1 observations to get high-spatial-resolution images of the Sun. In Sect. 2, we describe the details of the experiment. Reconstructed images acquired by the telescope are shown in Sect. 3. We draw the main conclusions of the experiment and describe new opportunities of the instrumentation in Sect. 4.

2 Experimental details

For the experiment, we modified the optical scheme of STT-1. A flat mirror was placed in the focal plane of the telescope. The reflected beam passed through a camera and was focused at a detector. We used a commercial Granit-11M objective with a 200 mm focal length as a camera. The CMOS ZWO ASI120MM-S detector was used to image the Sun at a high frame rate. The detector had a rectangular 1280 × 960 pixel sensor with a pixel size of $3.75 \times 3.75\ \mu m^2$. The highest frame rate was 29 frames per second at full resolution. In order to prevent saturation of the detector, we set a neutral density filter in front of the entrance window of the detector. The typical exposure was 100–200 μs. The most obvious shortcoming of the optical scheme was the focal length of the camera: the image of the solar surface was smaller than the size of the sensor with a 200 mm focal length. On the other hand, the commercial camera allowed us to focus the image on the detector without changing the distance between the camera and the detector.

The entire observations of a certain part of the solar surface commonly lasted for several tens of seconds. Up to several thousands of frames were acquired during this time. The data was recorded in a 16-bit depth video format. Before the observations, a calibration of the optics was performed: the image of the Sun was continuously shifted in the focal plane of the telescope by coelostat mirrors. All the acquired frames were averaged to get one final image. We used this image as a flat-field for data preprocessing.

The mathematical processing of the short-exposure frames was performed by the amateur AutoStakkert[1] package that uses the shift-and-add method to reconstruct distorted images. Briefly, this process can be described as follows: each frame is divided into small overlapping rectangular patches. Then the corresponding patches in each frame are shifted to get the best coincidence between them. The final image is reconstructed from these shifted patches. AutoStakkert also applies the lucky imaging technique: only the best frames are selected from the series for processing. In practice, depending on the quality of the acquired data, 50 to 80 percent of the frames were used in the processing. A wavelet-filtration of the reconstructed images was performed by the amateur RegiStax[2] software.

We also used the Kiepenheuer-Institut Speckle Interferometry Package (KISIP, Wöger et al., 2008) to process the data. This package uses a speckle-interferometry technique and is intended for the reconstruction of the images acquired by solar telescopes with adaptive optics. Remarkably, both approaches of image reconstruction yielded quite similar structures at the solar surface. Consequently, we suppose these structures to really exist on the Sun rather than being artefacts of data processing.

Depending on the quality of the raw data and the package applied, we used from several tens up to hundreds of frames to reconstruct the image. This number of images corresponds to the observation time of approximately 30 s. During this time, the solar structures that can be revealed in our images change insignificantly.

3 Results

We made the experiment during October and November, 2022. The best raw images of the Sun were acquired in the light gaze morning at an air temperature of about 15 degrees Celsius. During certain days, quite good images could be observed during the entire daytime. A subjective estimation of the quality was performed by observing the granulation in the solar disk center: under good conditions, the granulation could be revealed after a single exposure in the majority part of the quiet-Sun images.

An example of a reconstructed image of NOAA active region 12893 is shown in the left panel of Fig. 1. The active region was observed with STT-1 on November 6, 2021. By the time of observations, the active region was a unipolar sunspot located near the disk center. A clear light bridge divided the sunspot umbra into several parts. The continuum intensity image of the active region, which was taken by the Helioseismic and Magnetic Imager (HMI, Schou et al., 2012) onboard the Solar Dynamics Observatory (SDO, Pesnell et al., 2012), is shown in the right panel of Fig. 1 for comparison. SDO/HMI is a refractor with the objective lens

---

[1] https://www.autostakkert.com/

[2] https://www.astronomie.be/registax/

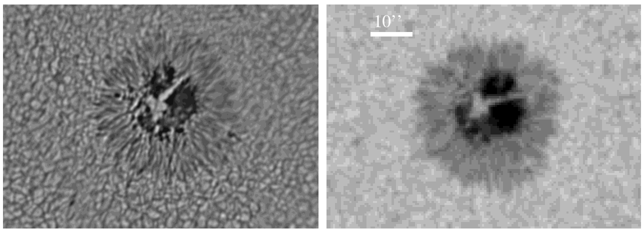


Fig. 1. The images of NOAA active region 12893 acquired on November 6, 2021 at 06:37 UT with STT-1 (left panel) and SDO/HMI (right panel). The white horizontal line in the right panel corresponds to 10$''$ at the solar surface. The image in the left panel was reconstructed with the amateur software AutoStakkert and RegiStax.

of 140 mm in diameter (Schou et al., 2012). Using Equation (1), we can estimate that the maximal spatial resolution of SDO/HMI is 1.1$''$ at 617 nm operating wavelength. One can see that the STT-1 images provide more details in the umbra and the penumbra of the active region. Recall that the spatial resolution due to seeing is rarely better than 2$''$ during daytime in the place where CrAO is located. Hence, the approaches of image reconstruction allows us to improve the spatial resolution of STT-1 observations at least by several times.

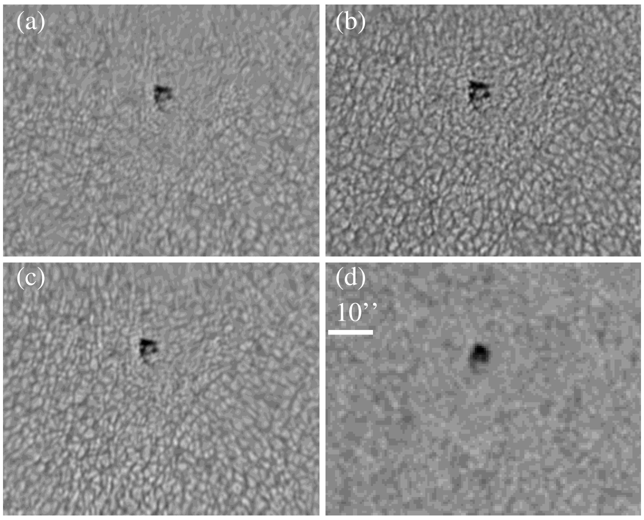


Fig. 2. The images of a pore observed on October 23, 2021 at 07:07 UT with STT-1 (panels a-c) and SDO/HMI (panel d). The images in the upper panels were reconstructed using the KISIP code in BBSO (panel a) and NAOC (panel b). The image in panel (c) was reconstructed using the amateur AutoStakkert package with further wavelet filtration by the RegiStax software. One can see a very good correspondence between the details in the images. The white horizontal line in panel (d) corresponds to 10$''$.

Another example of image reconstruction of a small pore observed on November 23, 2021 is presented in Fig. 2, panels (a) – (c). The image in panel (a) was obtained using the KISIP code in BBSO by Prof. V.B. Yurchyshyn. The image in panel (b) was also reconstructed by the KISIP code operated at the National Astronomical Observatories of China (PRC). Different image contrast is due to different settings of the package and different number of raw images used in the processing. Nevertheless, quite similar structures in both panels are seen in the pore and in the quiet-Sun regions. The image in panel (c) was acquired using the amateur AutoStakkert package with further wavelet filtration by the RegiStax software. A perfect agreement between the details in the images in panels (a) – (b) can be seen. The same region of the solar surface taken by SDO/HMI is shown in panel (d) for comparison.

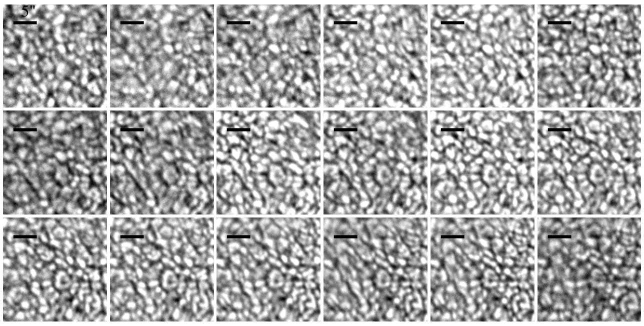


Fig. 3. A quiet-Sun region near the disk center observed with STT-1 on October 14, 2021 between 12:12 UT and 12:21 UT. The black horizontal line in each panel corresponds to 5$''$. The series of images shows the evolution of solar granulation during 9 minutes.

Finally, in Fig. 3 we show the evolution of a granulation of a small quiet-Sun region observed with STT-1 on October 14, 2021 between 12:12 UT and 12:21 UT. A notable ring-shaped large granule is clearly seen in the bottom and middle panels. In the series of images, we can track its formation and dissipation.

4 Conclusions

The described experiment revealed that STT-1 can be used to acquire high-spatial-resolution images of the Sun. We may conclude that the quality of optical surfaces of the telescope is good enough. Based on the visual analysis of the reconstructed images, we suppose that the processing of short-exposure images allows us to get a resolution limit of the telescope of about 0.3$''$. For a reliable solar image reconstruction, hundreds of frames are required. Using state-of-the-art high-speed detectors, we can take these frames in about several seconds. Hence, the cadence of the data may be of about 1–2 s.

Without any doubts, an important factor is seeing. During a month of observations, approximately two thirds of clear-sky days were appropriate for high-resolution observation at least in the morning. According to the results in Gaze (1948), the seeing is better during the summer as compared to October and November. Hence, we presume high-resolution observations to be possible during 5 to 6 months a year.

The experiment demonstrated the importance of the STT-1 modification aimed at solar observations in the continuum. A mirror slit can be installed instead of the flat mirror used in the experiment. This decision will provide a lot of benefits. First, simultaneous spectropolarimetric and continuum intensity observations of the solar surface will become possible. Second, the current position of the slit can be seen in the continuum intensity images. Third, continuum observations can be used for a fast adjustment of the diagonal mirror slope in order to stabilize the image of the Sun on the slit and to guide the telescope.

The experiment allowed us to define our requirements to the continuum intensity imager. Beside matching of the optical elements, we need to use a narrow-band 10-angstrom wide interference filter. Different spectral lines are formed within different heights in the solar atmosphere. We can use spectral lines that are more sensitive to temperature variations in the atmosphere, for instance, the TiO 7057 Å molecular series. In this case, we could increase the contrast of the solar features and to improve the quality of raw images. Besides, it is worth using a low-noise detector: the noise of the detector is clearly revealed in the images reconstructed by the KISIP code (Fig. 2b).

If we succeed in installing the continuum intensity imager and start new types of observations, we will be able to develop new scientific studies at CrAO. High-spatial-resolution and high-cadence data can be used to analyze the fine structure of sunspots, pores, faculae, granules, as well as their dynamics (see, for example, Fig. 3). In the case of using the narrow-band filters for a certain spectral line, for instance H_α or Na D, we can extend our studies to both the photosphere and the chromosphere.

Acknowledgements

We are deeply grateful to Prof. V.B. Yurchyshyn (BBSO, USA) for the speckle-reconstruction of STT-1 observations by the KISIP package at BBSO. SDO is part of NASA's "Living with a star" program. The HMI data are courtesy of NASA/SDO and HMI science team (provided by JSOC[3]).

References

Fried D.L., 1966. Journal of the Optical Society of America (1917–1983), vol. 56, p. 1372.

Gaze V.F., 1948. Izv. Krymsk. Astrofiz. Observ., vol. 3, pp. 99–108. (In Russ.)

Goode P.R., Coulter R., Gorceix N., Yurchyshyn V., and Cao W., 2010. Astron. Nachr., vol. 331, p. 620.

Liu Z., Xu J., Gu B.-Z., Wang S., You J.-Q., Shen L.-X., et al., 2014. Res. Astron. Astrophys., vol. 14, pp. 705–718.

Pesnell W.D., Thompson B.J., Chamberlin P.C., 2012. Solar Phys., vol. 275, p. 3.

Rimmele T.R., Warner M., Keil S.L., Goode P.R., Knölker M., Kuhn J.R., et al., 2020. Solar Phys., vol. 295, p. 172.

Schou J., Scherrer P.H., Bush R.I., Wachter R., Couvidat S., Rabello-Soares M.C., Bogart R.S., et al., 2012. Solar Phys., vol. 275, p. 229.

von der Luehe O., 1984. Optical Society of America, Journal, A: Optics and Image Science, vol. 1, p. 510.

Wöger F., von der Lühe O., Reardon K., 2008. Astron. Astrophys., vol. 488, p. 375.

---

[3] https://jsoc.stanford.edu/