New vacuum solar telescope and observations with high resolution *

Zhong Liu¹, Jun Xu¹, Bo-Zhong Gu², Sen Wang³, Jian-Qi You¹, Long-Xiang Shen³, Ru-Wei Lu¹, Zhen-Yu Jin¹, Lin-Fei Chen¹, Ke Lou¹, Zhi Li¹, Guang-Qian Liu¹, Zhi Xu¹, Chang-Hui Rao⁵, Qi-Qian Hu², Ru-Feng Li¹, Hao-Wen Fu¹, Feng Wang⁶, Men-Xian Bao¹, Ming-Chan Wu¹, and Bo-Rong Zhang¹

¹ Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China; lz@ynao.ac.cn
² Nanjing Institute of Astronomical Optics & Technology, National Astronomical Observatories, Chinese Academy of Sciences, Nanjing 210042, China
³ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
⁴ Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China
⁵ Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China
⁶ Kunming University of Science and Technology, Kunming 650500, China

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Abstract The New Vacuum Solar Telescope (NVST) is a one meter vacuum solar telescope that aims to observe fine structures on the Sun. The main goals of NVST are high resolution imaging and spectral observations, including measurements of the solar magnetic field. NVST is the primary ground-based facility used by the Chinese solar research community in this solar cycle. It is located by Fuxian Lake in southwest China, where the seeing is good enough to perform high resolution observations. We first introduce the general conditions at the Fuxian Solar Observatory and the primary science cases of NVST. Then, the basic structures of this telescope and instruments are described in detail. Finally, some typical high resolution data of the solar photosphere and chromosphere are also shown.

Key words: telescopes — instrumentation: adaptive optics — instrumentation: spectrographs — techniques: high angular resolution — Sun: magnetic fields

1 INTRODUCTION

The New Vacuum Solar Telescope (NVST) is a vacuum solar telescope with a 985 mm clear aperture. It is the primary observing facility of the Fuxian Solar Observatory (FSO). The location of FSO is 24°34′48″N and 102°57′01″E, on the northeast side of Fuxian Lake (Fig. 1), with an altitude of 1720 m above the sea level. The average seeing (in terms of the Fried parameter r₀) at FSO obtained in the period from 1998 to 2000 is about 10 cm (Fig. 2). The sunshine duration at FSO is about 2200 hours per year. The average wind velocity is 6 m s⁻¹, and more than 75% of wind around FSO is from the lake and toward the telescope (Lou et al. 2001). The weather parameters have been measured by an automatic meteorological station. The seeing parameters include the scintillation and the Fried

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parameter, and were measured by a scintillometer and a Solar Differential Image Motion Monitor (SDIMM) that was first developed by the FSO team (Liu & Beckers 2001; Beckers et al. 2003).

The early science investigations carried out at NVST focused on spectral observations because NVST was originally proposed mainly as a ground-based large scale spectrometer associated with the Chinese one meter Space Solar Telescope (Deng & Zhang 2009). The original primary working mode of NVST was multi-band spectral observations, including measurement of the Stokes parameter of the solar lines that are sensitive to the magnetic field. The good seeing at FSO encouraged the FSO team to expand the scientific goals to high resolution observations in order to cover more topics related to open issues and hot topics. Now, the scientific goals of the telescope include observing the Sun with very high spatial and spectral resolutions in the wavelength range from 0.3 to 2.5 µm; detecting small-scale structures and fine details in the evolution of the solar magnetic fields and their coupling to the plasma; investigating energy transfer, storage and release in the solar atmosphere, such as coronal heating, the triggering of a solar eruption, and other key questions related to solar activities. Now, as the primary optical and near infrared solar telescope used by the Chinese solar re-

![Fig. 1](image1.jpg) **Fig. 1** Building (*left*), telescope and the wind screen (*right*) at NVST.

![Fig. 2](image2.jpg) **Fig. 2** Curve showing variations in seeing ($r_0$) at FSO during the period from September 1999 to September 2000.
search community (Fang 2011; Wang & Ji 2013), NVST is required to undertake more goals related to science and technology, including necessary experiments for key technologies of developing next generation solar telescopes (Liu et al. 2012).

In the next section, we briefly describe the basic structure of NVST. The instrumentation of the telescope is introduced in Section 3. We display some high-resolution observational data obtained by NVST in Section 4.

2 THE BASIC STRUCTURE OF NVST

2.1 Mechanism and Building

The whole building that contains NVST is a complex system and mainly includes the vacuum telescope, an instrument platform, vertical spectrometers and other necessary equipment, such as a wind screen and a moveable dome.

Figure 3 is a 3-D sketch of the whole building. The telescope is installed on the top-front part of a building that is 16 meters high. The building is constructed on a large rock, very close to the lake (Fig. 1 left). The roof of the building is designed to have a shallow pool filled with water that cools the floor. In most cases, the telescope works in the open air in order to maintain good local seeing. The moveable dome will open and move to another side of the building while the telescope is working. A louvered windscreen fences the telescope against wind and guides wind toward the floor, reducing turbulence near the ground. The windscreen can move and rise automatically according to the wind direction and the different attitudes of the telescope. The telescope and the instrument platform are individually installed on two independent piers to avoid crosstalk of vibration. The dome and the windscreen are located directly on top of the building.

The mounting system of NVST is an alt-azimuth structure (Fig. 1, right). The telescope should rotate along its axes to counter Earth’s rotation while tracking the Sun. The alt-azimuth mounting means stabilization and small wind resistance is necessary. It also has an observational blind spot and nonuniform image rotation. The blind spot associated with NVST is less than two degrees from the zenith point. Considering the latitude of the Tropic of Cancer is 23.5° and the latitude of FSO is 24.5°N, there is no blind spot for solar observation except for several days around the summer solstice. The image rotation is caused by the asymmetric turning of the optical axis and the relative rotation between mirrors. In order to eliminate image rotation, the instrument platform and the vertical spectrometers should rotate around the primary optical axis with nonuniform velocity. The rotations of the telescope and instrument platform are driven by several fine electric motors via friction drive devices.

The pointing accuracy of NVST is high enough that it can point to any region on the solar disk with an accuracy of several arcseconds. The tracking accuracy of NVST is 0.3″ (RMS). The pointing and tracking accuracies are maintained by two control loops. The sensors for the outer control loops are two highly accurate angle encoders installed on the altitude axis and the azimuth axis. The inner active control loop is an optical Auto Guide System (AGS). The AGS is attached to a small guide telescope which is fixed on the tube of NVST. The sensor that is part of the AGS is a 4k by 4k CMOS camera. NVST can steadily track the Sun over several hours once the AGS starts operating. The key functional parameters describing the NVST are displayed in Table 1.

2.2 Optical System of NVST

NVST is designed to be a vacuum telescope in order to reduce turbulence in the system. Figure 1 (right) and Figure 4 display the telescope and its optical layout. An optical window (W1) with a diameter of 1.2 meters is placed on the top of the vacuum tube to keep the air pressure inside the tube lower than 70 Pa. The optical system after W1 is a modified Gregorian system with an effective focal length of 45 m. The primary mirror is a parabolic imaging mirror with a clear aperture of 985 mm.
Table 1 Key Parameters Describing the NVST

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear aperture</td>
<td>985 mm</td>
</tr>
<tr>
<td>Field of view</td>
<td>3′</td>
</tr>
<tr>
<td>Focal length (EEFL) at F3</td>
<td>45 m</td>
</tr>
<tr>
<td>Spectral range</td>
<td>0.3 ~ 2.5 μm</td>
</tr>
<tr>
<td>Tracking accuracy</td>
<td>&lt; 0.3′</td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>&lt; 5″</td>
</tr>
<tr>
<td>Image quality (80% EE of PSF)</td>
<td>&lt; 0.4″ at 550 nm</td>
</tr>
<tr>
<td>Blind area</td>
<td>&lt; 2°</td>
</tr>
<tr>
<td>Vacuum pressure inside telescope tube</td>
<td>&lt; 100 Pa</td>
</tr>
</tbody>
</table>

Table 2 Key Parameters Describing the Optical Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Size and Shape</th>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Φ1200, infinity, Flat</td>
<td>BaK7</td>
<td>Vacuum window</td>
</tr>
<tr>
<td>M1</td>
<td>Φ985, R4800, Paraboloid</td>
<td>Glass-ceramic</td>
<td>Primary mirror</td>
</tr>
<tr>
<td>M2</td>
<td>Φ258, R980, Ellipsoid</td>
<td>Glass-ceramic</td>
<td>Secondary mirror</td>
</tr>
<tr>
<td>M3</td>
<td>Φ225, R3238, Ellipsoid</td>
<td>Glass-ceramic</td>
<td>Focusing mirror</td>
</tr>
<tr>
<td>M4~M7</td>
<td>*, infinity, Flat</td>
<td>Glass-ceramic</td>
<td>Reflective mirrors</td>
</tr>
<tr>
<td>W2~W5</td>
<td>*, infinity, Flat</td>
<td>BaK7</td>
<td>Vacuum windows</td>
</tr>
</tbody>
</table>

* The sizes of these optical components are slightly bigger than the requirements.

There is a 3′ field diaphragm (heat stop) at the primary focus (F1) to prevent extra energy from entering the system. Unwanted light is reflected from the system through another vacuum window (W5) on the side of the vacuum tube. The secondary mirror (M2) converges light to an F/9 beam and focuses the light beam at the secondary focus (F2) where the calibration unit for polarization is installed. M4 is a small flat mirror that reflects light toward the horizontal direction. As the third imaging mirror, M3 converges light to the third focus (F3), after which there are three flat reflectors (M5-M7). The mirror M3 is also the focusing mirror for the whole system.

Table 2 displays more information about each optical component in the NVST.

The vacuum system consists of two vacuum tubes as the telescope should rotate on its altitude axis in addition to its azimuth axis. These two vacuum tubes are separated by two vacuum windows (W2 and W3). Most of the big optical components, including W1 through M4, are installed in the primary vacuum tube while the mirrors M5, M6 and M7 are installed in the secondary vacuum tube. After going through all the mirrors and windows, light from the Sun is focused and guided to a rotating instrument platform with a diameter of 6 meters, on which all imaging instruments, including the adaptive optics system, are installed. The photosphere and the chromosphere can be observed with high spatial resolution by these imaging instruments. Two vertical grating spectrometers with different dispersion powers are placed in a vertical hanging bracket (Figure 3) which is hung below the instrument platform and rotates along with the platform to eliminate image rotation.

The thermal control system used by NVST consists of two parts, a water-cooling system and a set of heat pipes installed between the F1 diaphragm and the wall of the vacuum tube. Although most of the extra energy can be reflected out from the system, some residual heat is still harmful to the F1 diaphragm and affects infrared observations. The heat pipes bring the residual heat to an exchanger connected to a water-cooling system. A circular water-cooling tunnel around W1 is designed to reduce image degradation caused by the radial temperature gradient of W1. Another method to decrease the influence of the radial temperature gradient is to enlarge the diameter of W1. Therefore, the diameter of W1 is designed to be 1200 mm, more than 200 mm larger than the diameter of the primary mirror. An air knife can also be installed at the edge of W1 as an optional device to maintain good mirror seeing.
The instruments that are utilized by NVST are designed for performing observations and studies related to the scientific goals. They are located either on the rotating instrument platform or on the frames of the vertical hanging bracket below the telescope (Fig. 3). These instruments basically consist of three groups according to their functions and working modes, and their arrangement in space is sketched in Figure 5. The first group includes the adaptive optics (AO) system and polarization analyzer (PA). The AO system is installed on the rotating platform before other instruments and the PA is placed right before the slit for the vertical spectrometers. The second group consists of all imaging instruments mounted on the rotating platform. The third group includes two vertical grating spectrometers placed in the hanging bracket below the rotating platform.
Fig. 5 Schematic descriptions of instrument arrangement that is part of NVST (Not to scale).

Fig. 6 The low order AO system and (left) the result of an observation obtained at 7058 Å (right).

Each instrument can work either individually or as a subsystem of the whole apparatus, which is connected to the telescope via mirrors M8 and M9 (Fig. 5). Here, M8 is a reflecting mirror and M9 is a beam splitter with high reflectance and low transmission. Different observing modes are achieved by various combinations of M8 and M9. The light beam from the telescope is first reflected into the AO system by M8. Then, it is sent to different instruments depending on the purposes of observers after going through the AO system. The light beam does not go through M9 if the purpose of observations is just imaging, and it will enter the imaging system directly after leaving the AO system. For spectral observations, the beam splitter M9 will be inserted into the optical path after the AO system. In this case, most photons are reflected down to the spectrometers, but some photons that enter the imaging system are used to monitor the slit position. For observations without AO, M8
is removed from the optical path. When replacing M9 by a reflector, all the photons are sent to the imaging system. If M8 and M9 are both removed from the optical path, the photons may directly enter the spectrometers.

3.1 Adaptive Optics System Used by NVST

The present AO system that is used by NVST is a low order system with only 37 actuators (Rao et al. 2012). It is placed before the other instruments but after F3 (Fig. 5). A Shack-Hartmann wavefront sensor with 37 sub-apertures is used to detect the wavefront by observing granulations or other obvious small structures on the photosphere, such as small sunspots or pores. The frame rate of the wavefront sensor is up to 800 frames per second (fps). The deformable mirror is a 40 mm glass mirror incorporating 37 piezoelectric transducer actuators. The first five orders of the Zernike aberrations that include 20 modes that describe the wavefront could be efficiently corrected by this system. The Strehl ratio of the corrected image is better than 0.5 when seeing is better than or equal to 10 cm. The left panel in Figure 6 displays some elements in the system, and that on the right shows the observational results obtained at 7058 Å in the case of good seeing.

3.2 Polarization Measurement

The basic approach to detecting a magnetic field with NVST is to measure the polarization by using the Zeeman effect. The main structure of the telescope before M4 is symmetrical, both optically and mechanically, in order to reduce extra instrument polarization or polarization crosstalk. For example, spiders that support the secondary mirror and the heat stop are in the shape of a cross rather than the simpler and the more easily adjusted shape of a tripod. The original design of the PA used for NVST was a system with fast modulation that used wave plates made of liquid crystal (Xu et al. 2006). The original proposal was to install these plates close to F2 which would enable high precision measurements of the solar polarization. Eventually, it turned out that this PA did not fit in the space allowed for the optical system of NVST. It has now been replaced by a rotating modulation system with classical wave plates. The present PA is placed before the slit of the spectrometer but the calibration unit is still installed close to F2. The whole polarization system is achromatic around both 5000 and 10 000 Å. Combining with the spectrometers, the system can conduct measurements of the Stokes parameters with high accuracy in both optical and near infrared bands, for example at 5324 and 10 830 Å. The PA and the calibration unit can be moved in or out of the optical path simultaneously or separately depending on the observing modes. The anticipated accuracy of the polarization measurement is expected to be better than $5 \times 10^{-3}$ after the ongoing installation and calibration are completed.

3.3 Imaging System

Observing fine structures in both the photosphere and the chromosphere is the main scientific goal of NVST. The imaging system is mounted on a rotating platform that is 6 meters in diameter. Its main structure is a multi-channel high resolution imaging system and consists of one channel for the chromosphere and two channels for the photosphere. The band used for observing the chromosphere is Hα (6563 Å). The bands for observing the photosphere are TiO (7058 Å) and the G-band (4300 Å). The Hα filter is a tunable Lyot filter with a bandwidth of 0.25 Å. It can scan spectra in the ±5 Å range with a step size of 0.1 Å. Connected to the optical splitters, all the channels can synchronously observe and record images. This means that the fine structures and their evolution in the photosphere and the chromosphere can be observed at the same time.

The whole system can work independently or work as a multi-channel AO imaging system by simultaneously operating with the AO system. In good seeing conditions, without AO, the resolution
of reduced photosphere images at the G-band can almost reach 0.1″ after being reconstructed with a statistical algorithm that achieves high resolution. The time cadence of the reconstructed images is about 10 s.

Table 3 lists the key parameters describing the current imaging system that is part of NVST. Some cases observed recently are summarized as follows (see also Fig. 7): photospheric bright points, fine structures of solar activities, microsolar activities such as microfilaments and their evolution, and similar phenomena. These cases are forefront topics of modern solar physics and need high angular resolution near the diffraction limit of NVST.

3.4 Spectrometers

The measurement of spectra from the solar atmosphere is another important goal that can be accomplished at NVST. This is the primary method for detecting magnetic and velocity fields in the solar atmosphere. Besides the traditional scientific goals, small scale structures in the photosphere and the chromosphere can be detected by spectrometers combined with the AO system. These small structures include bright points, dynamic features with plasma inside a flux tube, fine structures of the quiescent filament and so on.

The spectrometers that are part of NVST include a multi-band spectrometer (MBS) and a high dispersion spectrometer (HDS). They are placed on the vertical hanging bracket right below the rotating platform, which rotates along with the platform and acts as a huge image de-rotator (Fig. 3).
Fig. 8 3-D sketch of the spectrometers (left, not to scale), and some observational results (right). The spectra of a quiet region around 6563 Å and 8542 Å observed by MBS. The spectra of a small sunspot around 15 600 Å observed by HDS.

<table>
<thead>
<tr>
<th>Table 4 Key Parameters Describing the Spectrometers</th>
</tr>
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<tbody>
<tr>
<td>Spectrometer</td>
</tr>
<tr>
<td>Grating (mm⁻¹)</td>
</tr>
<tr>
<td>Blazed angle (°)</td>
</tr>
<tr>
<td>Focal length of imaging mirrors (m)</td>
</tr>
<tr>
<td>Focal length of collimating mirror (m)</td>
</tr>
<tr>
<td>Effective size of grating (mm)</td>
</tr>
<tr>
<td>Primary lines (Å)</td>
</tr>
<tr>
<td>Dispersion (mm/Å)</td>
</tr>
<tr>
<td>Resolution (λ/Δλ)</td>
</tr>
<tr>
<td>Spectrum range (Å)</td>
</tr>
</tbody>
</table>

An adjustable slit for the spectrometers is installed at the center of the rotating platform. The width and orientation of the slit can be changed for different spectrometers and various science cases. Before the slit, as described in the previous section (Fig. 5), about 10% of the photons are redirected into the imaging system to display the image and the position of the slit. The orientations of the two spectrometers are perpendicular to one another (see left panel of Fig. 8), and they share the same slit described above. Switching the use of the spectrometer from MBS to HDS is accomplished by rotating the slit and removing the collimating mirror which is part of MBS. This operation cannot be performed during observations, and should be completed beforehand. Therefore, the two spectrometers cannot work simultaneously.

The gratings used by the two spectrometers are different. We are using a blazed grating for MBS and an echelle grating for HDS. The two gratings are both installed on the reverse side of the rotating platform, and face the collimating mirrors (see Fig. 5). Imaging mirrors and collimating mirrors are placed on the vertical hanging brackets. Detectors are all placed face down on the central part of the rotating platform to record the spectrograms focused by the imaging mirrors. The huge space taken by spectrometers minimizes the scattered light. Important parameters describing the MBS and HDS are shown in Table 4, and some observational results obtained by the two spectrometers are
displayed in the right panel of Figure 8. These results are preliminary and are calibrated in order to correct the obvious aberrations and remove the visible interference fringes (Wang et al. 2013).

We note here that the pixel size of each instrument is not listed in Tables 3 or 4, because even the same instrument needs different detectors for different cases. Usually, various detectors, such as the CCD, CMOS and EMCCD, have different formats and pixel sizes. So, values of these parameters will be included in the header of the files for observational data, and should be changed for different cases.

3.5 Upgrade of Instruments

The instruments described above are currently installed on NVST, but the present performance of the facility will be improved in the future. Upgrading these instruments is always under consideration, and the consequent deployment would follow when it becomes necessary and technically doable. Furthermore, sufficient space for new instruments on the 6 m rotating platform has also been allotted, and any newly developed instruments could be installed when the relevant topics or fields need to be studied. In addition to the platform, the large hanging bracket could accommodate more imaging mirrors as well, which would allow the spectrometers to observe more lines if needed.

The ongoing upgrade of instruments involves the AO system and the multi-channel imaging system. First, a high order AO system with 127 actuators is under construction, and will replace the present one as it completes its planned work. Then, two new channels with tunable Lyot filters will be added at 10 830 and 3933 Å bands. After this upgrade, NVST will be able to do more comprehensive observations of the chromosphere with higher spatial resolution. Besides the process of upgrading, more proposals have been put forward. An integral field spectrograph with about 400 fibers is in the process of development, and its spectral resolution will be up to 100 000. A magnetograph with high spatial resolution has also been designed in order to match the resolving power of the current multi-channel imaging system. NVST may also be the primary laboratory for instruments that will be installed on the next generation of solar telescopes, such as the Chinese Giant Solar Telescope (Liu et al. 2012). Some new technologies and new instruments will be tested and examined on NVST, including multi-conjugate adaptive optics (MCAO; Beckers 1988), a two-dimensional real-time spectrograph (Ai 1993) and a large field fiber array (Dun & Qu 2012).

4 HIGH RESOLUTION OBSERVATIONS MADE BY NVST

The random, rapid image degradation induced by the Earth’s turbulent atmosphere is a major problem with ground-based telescopes. The image degradations observed by NVST could not be perfectly corrected by its current low order AO. So, in order to acquire images with high spatial resolution, with or without AO, the raw data from NVST should be reconstructed by a high resolution imaging algorithm. The reduced data from NVST are classified into two levels. The level1 data are processed by frame selection (lucky imaging) (Tubbs 2004). The level1+ data are reconstructed by speckle masking (Weigelt 1977; Lohmann et al. 1983) or iterative shift and add (Liu et al. 1998).

A high resolution image is normally reconstructed from at least 100 short exposure images. Each raw image is divided into many 5 square arcsecond segments to match the isoplanatic angle of Earth’s atmosphere. Then, 100 raw images are divided into a number of subsequences. A high resolution subimage is reconstructed from a subsequence which contains 100 small segments. Finally, all the reconstructed subimages are combined to form an entire high resolution image (Fig. 9). The seeing parameter that is needed for reconstruction is calculated by the spectral ratio (von der Luehe 1984) or measured by SDIMM. The time cadence of a reconstructed image is limited by the observation time of a raw data sequence. The scanning and readout speed of all the detectors on NVST are fast enough to insure the highest time cadence is smaller than 10 s.

High resolution observation of an active region is the primary science task of NVST during the 24th solar cycle. After reconstruction, the spatial resolution of an image of the photosphere (G-band,
**Fig. 9** Flow chart showing the process of reconstructing a high resolution image.

**Fig. 10** High resolution image of the photosphere showing AR 11154. Level1+ data are taken at 7058 Å.

**Fig. 11** G-band bright points associated with the quiet Sun. Level1+ data are taken at 4300 Å.
Fig. 12 Quick evolutions of the active filaments during a flare eruption on 2012 October 25 (AR 11598). Level1+ data are taken at the Hα line center.

Fig. 13 A quiescent prominence and a rapidly rising flow that occurred on 2013 February 15. Level1 data are taken at the Hα line center.

4300 Å) could reach nearly 0.1" in good seeing conditions, and the spatial resolution of an image of the chromosphere (Hα, 6563 Å) is better than 0.3". With such a spatial resolution, NVST can resolve many fundamental structures in the photosphere and chromosphere within a 3' field of view (Xu et al. 2014).

Figures 10 to 14 are some high resolution reconstructed images taken at NVST. These results represent different objects and various science cases. All the results have been reconstructed by the above high resolution imaging algorithms. Figure 10 is a high resolution image of the photosphere
Fig. 14 The fine structures around the small sunspots. Level1+ data are taken at the H$_\alpha$ blue wing ($-0.8$ Å).

showing a typical small active region in the TiO band. In this image, details of the photosphere, such as bright points in the umbra, fibers in the penumbra and bright points between granules, are all clearly resolved. This kind of data is very useful for research on the fine structures and evolutions of active regions. Figure 11 is another high resolution image of the photosphere featuring the quiet Sun in the G-band. It shows the high resolving power of NVST, and the spatial resolution of this image almost reaches the diffraction limit of NVST. Such data can be used to study the dynamical properties of fine features in the photosphere and it is also very important to look for photospheric footpoints corresponding to chromospheric activities. Figure 12 includes several high resolution H$_\alpha$ images of AR 11598 and the surrounding filaments. It shows the quick evolutions of active filaments during a flare eruption. The primary target of Figure 13 is a quiescent prominence at the edge of the solar disk. The quick formation process of another small prominence is also clearly shown. In addition, Figure 13 shows that scattering in NVST is low enough to observe objects that have low contrast. Figure 14 includes two off-band H$_\alpha$ images. Spicules and Ellerman bombs around active regions are the targets of this observation. It should be noted that, as seeing at FSO is normally stable for several hours, sequences of data with high resolution taken by NVST are usually long enough to cover most short term solar activities, such as classical flares and the process of filament eruption.

5 SUMMARY

The observational data acquired at NVST, including images and movies, are now available [http://fso.ynao.ac.cn](http://fso.ynao.ac.cn). As one of the current large solar telescopes in the world, NVST achieves its designed performance in terms of high resolution observations. Considering that it is located between Europe and America, NVST could work in combination with other large solar telescopes (Scharmer et al. 2003; Schmidt et al. 2012; Goode & Cao 2012) to form a global high resolution observation network. NVST is expected to contribute some original discoveries in the near future, and it is necessary to upgrade the facility with more high-precision instruments, especially instruments for measuring the magnetic field.

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