The AIMS Site Survey Postprint

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Abstract

This paper reports site survey results for the Infrared System for the Accurate Measurement of Solar Magnetic Field, especially in Saishiteng Mountain, Qinghai, China. Since 2017, we have installed a weather station, spectrometers for precipitable water vapor, and Solar Differential Image Motion Monitor, and have carried out observations on weather elements, precipitable water vapor, and daytime seeing conditions for more than one year in almost all candidates. At Mt. Saishiteng, the median value of daytime precipitable water vapor is 5.25 mm and its median value in winter season is 2.1 mm. The median value of the Fried parameter of daytime seeing observation at Saishiteng Mountain is 3.42 cm. Its solar direct radiation data show that solar average observable time is 446 minutes per day and premium time is 401 minutes per day in 2019 August.

Full Text

Preamble

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The AIMS Site Survey

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Abstract

This paper reports site survey results for the Infrared System for the Accurate Measurement of Solar Magnetic Field (AIMS), with particular focus on Saishiteng Mountain in Qinghai, China. Since 2017, we have installed a weather station, spectrometers for precipitable water vapor, and a Solar Differential Image Motion Monitor (S-DIMM), and have carried out observations of meteorological elements, precipitable water vapor, and daytime seeing conditions for more than one year at nearly all candidate sites. At Mt. Saishiteng, the median value of daytime precipitable water vapor is 5.25 mm, and its median value in winter is 2.1 mm. The median value of the Fried parameter from daytime seeing observations at Saishiteng Mountain is 3.42 cm. Solar direct radiation data show that the average solar observable time is 446 minutes per day and premium time is 401 minutes per day in August 2019.

Key words: site testing – atmospheric effects – methods: analytical

1. Requirement for AIMS Candidate Sites

The Infrared System for the Accurate Measurement of Solar Magnetic Field (AIMS) is a 1 m telescope dedicated to measuring the solar magnetic field in the mid-infrared waveband using a Fourier Transform Spectrometer with high spectral resolution. To maximize AIMS observation performance, several astronomical environmental factors were considered in the site survey investigation.

First, since AIMS observes the Sun at Mg I 12.3 m, it requires very low precipitable water vapor, as atmospheric water vapor content strongly impacts transparency in infrared and submillimeter domains (Kerber et al. 2012). Second, daytime seeing conditions must be measured to obtain good image quality, which is closely related to AIMS performance. While nighttime seeing conditions are typically measured using Differential Image Motion Monitors (DIMM) such as at the European Southern Observatory in Chile (Sarazin & Roddier 1990), daytime seeing conditions can be measured using Solar Differential Image Motion Monitors (S-DIMM) as demonstrated at Fuxian Lake, China (Liu & Beckers 2001) and at TUG, Turkey (Özişik & Ak 2004). Third, AIMS requires maximum possible solar observable time.

The site testing investigation for AIMS began in 2016 and was conducted in two phases. In Phase I (2016–2018), we primarily considered well-established stations with good accommodation and infrastructure due to limited construction time. Consequently, Ali in Tibet, Nanshan station in Xinjiang, Delingha station in Qinghai, and Daocheng in Sichuan were selected as the first four primary candidate sites. Nanshan and Delingha are well-developed stations with good accommodation. Ali station, at 5100 m above sea level, has poor logistics and tough living conditions. The daytime site testing survey at Daocheng has been conducted for more than one year (Song et al. 2018). Weather stations were installed at Nanshan, Ali, and Delingha stations, and a precipitable water vapor spectrometer was deployed at Delingha Station.

In Phase II (2018–2020), we focused site testing observations on Saishiteng Mountain (38°36 24 N, 93°53 45 E, altitude 4200 m) located on the northern edge of the Qaidam basin in Qinghai province [Figure 1: see original paper]. It lies 50 km east of Lenghu town (the only inhabited town at 2750 m altitude) in an arid climate region. In November 2018, an S-DIMM was deployed and daytime seeing observations were conducted for more than one year. A 10 m observing tower was built on Saishiteng Mountain in November 2018 [Figure 2: see original paper].

In the following sections, we present weather element results in Section 2, precipitable water vapor in Section 3, S-DIMM configuration and processing methods in Section 4, daytime seeing results in Section 5, and discuss the site testing results in Section 6.

2. Weather Elements

At the Nanshan, Ali, Delingha, and Mt. Saishiteng sites, we carried out meteorological observations including five weather elements: temperature, relative humidity, wind speed and direction, and solar direct radiation. All elements were recorded at 1-minute intervals.

Wind speed is an important meteorological element related to seeing conditions. Figure 3 shows the monthly variation of wind speed at Mt. Saishiteng, with a median value of 3.2 m s^{-1} and a maximum speed of 26.34 m s^{-1}. Wind speed at Ali station is the highest, with a median value of 4.7 m s^{-1} and a maximum speed of 31.2 m s^{-1} (Figure 4). Table 1 summarizes wind speed statistics for the four sites, among which Delingha station recorded the lowest median value of 1 m s^{-1}, while the median value at Nanshan station is 2.4 m s^{-1}.

Figure 5 shows the monthly temperature variation at Mt. Saishiteng during July 27, 2019–June 5, 2020, with a median value of −6.5°C, an average value of −5.0°C, a maximum temperature of 19.2°C, and a minimum temperature of −22°C. The monthly average temperature is shown in Table 2. The monthly variation of relative humidity at Mt. Saishiteng is shown in Figure 6, with a median value of 40.3% and an average value of 45%.

The total solar irradiance (TSI) is the intensity of solar radiation outside Earth's atmosphere, with a constant value of approximately 1361 W m^{-2} (Kopp 2021). Due to atmospheric absorption, the intensity of solar direct radiation is usually lower than 1200 W m^{-2} at Earth's surface. On clear days, the maximum solar irradiance indicates the absorption (or extinction) of the local atmosphere. On cloudy days, solar direct radiation reflects cloud thickness along the path from observer to Sun, regardless of cloud cover elsewhere in the sky. Therefore, we can determine whether and for how long the Sun can be observed from solar direct radiation data. Based on our experience, a solar telescope can observe the Sun continuously when solar direct radiation exceeds 500 W m^{-2} and intermittently when solar irradiance ranges between 300 and 500 W m^{-2} due to clouds or fog. It is difficult to observe the Sun normally when solar direct radiation falls below

300 W m^{-2}. In this paper, we define solar premium time as when solar direct radiation exceeds 500 W m^{-2} and observable time as when it exceeds 300 W m^{-2}.

The solar direct radiation meter used in AIMS site testing contains a thermoelectric pile that measures solar irradiance within a 5° field of view in the spectral range 300–3000 nm. In the early phase, a semi-automatic tracking system was used to follow the Sun at Nanshan, Ali, and Delingha stations. It tracked the Sun automatically in right ascension at 15°/hr but required manual adjustment in declination. Later we found its performance was poor without dedicated personnel to adjust the tube pointing when the Sun's declination varied or during occasional power outages.

Figure 7 shows the monthly solar irradiance distribution in June 2017 at Delingha station, with an average premium time of 296 minutes (5.95 hr) and an observable time of 360 minutes (6 hr) per day. The blue and red horizontal lines indicate the 300 and 500 W m^{-2} thresholds for solar observable hours and premium hours, respectively.

At Mt. Saishiteng, we deployed a fully automatic solar tracking system that can follow the Sun with an accuracy of less than 1° when the Sun is above the horizon (Figure 8 top). Figure 9 shows the monthly solar irradiance variation at Mt. Saishiteng in August 2019, with an average premium time of 401 minutes (6.7 hr) per day and an observable time of 446 minutes (7.4 hr) per day. Table 3 lists monthly statistics of solar premium time, observable time, maximum irradiance, altitude, and observation dates for the four sites. Higher altitude correlates with higher maximum irradiance. At Mt. Saishiteng, the maximum solar irradiance is 1173 W m^{-2}. The atmospheric transparency at Ali is highest since its altitude (5100 m) is the greatest among all sites. The relatively low observable hours at Nanshan station may be partly due to setting some abnormal irradiance data appearing as 1999 W m^{-2} to zero.

3. Precipitable Water Vapor

Precipitable water vapor (PWV) can be measured by several methods including radiosonde balloons, ground-based and satellite radiometers, Sun photometers, lunar photometers, GPS receivers, Fourier transform infrared spectrometers, and others (Qian et al. 2019). In the AIMS site testing survey, precipitable water vapor was measured by a spectrometer that measures the H_2O absorption line centered at 935 nm. When the spectrometer tube points to the Sun, precipitable water vapor is calculated from intensities at 935 and 889 nm using the following function:

$$R = \frac{I_{935}}{I_{889}} = f(W)$$

where R is the residual intensity ratio between the intensity at 935 and 889 nm, and W is PWV.

PWV measurements at Nanshan station and Ali station were obtained on only a few days, which is not statistically significant. Precipitable water vapor observations were carried out every 30 minutes on clear days between May 2017 and June 2018 at Delingha station. Its monthly PWV variation is shown in Figure 10, with median values of $W = 11.5$ cm and $W_0 = 7.0$ cm. W indicates the actual PWV measured when the spectrometer points to the Sun, while W_0 indicates the corrected value of W to the local zenith—that is, $W_0 = W/a$, where a is the air mass.

Figure 11 shows the monthly variation of precipitable water vapor from November 2018 to June 2020 at Mt. Saishiteng, with median values of $W = 8.07$ mm and $W_0 = 5.25$ mm. In winter, Mt. Saishiteng's PWV is low, with a median W_0 of 2.1 mm. Figure 12 shows the hourly variation of PWV within a day on May 23, 2019, demonstrating that W values are high in early morning due to large optical thickness and reach their lowest values after the Sun passes the local meridian.

4. Daytime Seeing Observation

At Saishiteng Mountain, the S-DIMM is installed on a 10 m high tower whose pier stands separately from the platform (Figure 2). It consists of a Celestron C11 XLT telescope with a clear aperture of 280 mm and an F/10 focal ratio (Figure 8 bottom). Two holes were opened in the C11 telescope cover as sub-apertures and covered with Baader film with 10^{-5} transmission. The sub-aperture diameter is 5 cm and their separation is 22 cm. Two prisms with deviation angles of 10 were mounted in each sub-aperture. A 1/40 neutral density filter was installed before the focal plane. The CMOS camera is a ZWO ASI 174MM with a 1936 × 1216 pixel sensor, where each pixel corresponds to 0.44 arcseconds (see Table 4).

When measuring seeing conditions, solar images were recorded as AVI videos with 14 ms exposure time, from which 100 PNG files were extracted. First, an intensity distribution is drawn along a horizontal direction crossing the solar eastern or western limb. The intensity gradient profile of the solar limb along the horizontal direction follows a Gaussian curve. The positions of the two limbs are determined at the center using Gaussian fitting (Figure 13). The variation σ of the distance between the two limbs is calculated from differences in the positions of the two solar limbs.

The Fried parameter r_0 can then be calculated from the variation σ^2 (Sarazin & Roddier 1990):

$$\sigma^2 = 2K \left(\frac{\lambda}{D}\right)^2 \left(\frac{D}{r_0}\right)^{5/3}$$

or in simplified form (Tokovinin 2002):

$$r_0 = 0.185\frac{\lambda}{\sigma}\left(\frac{D}{d}\right)^{0.5}$$

where D is the sub-aperture diameter, K is the coefficient, and $b = d/D$ where d is the aperture separation.

Figure 14 shows the monthly variation of the Fried parameter r_0 at Mt. Saishiteng, with a median value of 3.4 cm. A total of 1935 seeing data points were taken every 30 minutes via remote control on each clear day from November 7, 2018 to June 5, 2020, except when site testing instruments were offline or experiencing outages. Figure 15 shows the hourly variation of the Fried parameter on May 23, 2019, demonstrating that very good seeing conditions appear in early morning when the atmosphere is less disturbed by sunshine.

Figure 16 shows the distribution histogram with cumulative frequency of the daytime Fried parameter, indicating it peaks at 3.2 cm, with 90% of values less than 5.6 cm, 70% less than 4.3 cm, and 30% less than 2.7 cm. To explore the relationship between seeing condition r_0 and wind parameters, we plot the distribution of Mt. Saishiteng's seeing condition against wind speed (Figure 17(a)) and wind direction (Figure 17(b)) during measurements. This shows an almost isotropic distribution of the Fried parameter r_0, indicating little correlation with wind direction or speed.

5. Discussion

For AIMS observations in the mid-infrared waveband, PWV is the essential parameter among all site testing factors. Delingha station and Mt. Saishiteng are both located in western Qinghai Province, approximately 400 km apart, but PWV at Delingha is higher than at Mt. Saishiteng. One reason is their different altitudes (approximately 1000 m difference). Another possible factor is that Delingha is located near the Bayin River basin.

Our PWV measurement method is less accurate than commercial Low Humidity and Temperature Profiling Radiometers (LHATPRO). For comparison, the median PWV is about 0.52 mm at Muztagh-ata in Xinjiang and 2.1 mm at Daocheng in Sichuan (Feng et al. 2020), while the median PWV at the European Southern Observatory at Paranal, Chile is 2.5 mm (Kerber et al. 2012).

At Mt. Saishiteng, the average observable time per day in August 2019 is about 7.4 hours, corresponding to approximately 2701 observable hours per year. The highest solar radiance of 1103 W m^{-2} indicates high sky transparency at Mt. Saishiteng. Living and working conditions are tougher at Ali station (5100 m altitude), though it has the highest solar radiance of 1173 W m^{-2}. At Delingha station, the average observable time per day was 6 hours in June 2017.

For a 1 m telescope observing the Sun in the infrared band around 12.3 m, the median Fried parameter r_0 of 3.4 cm at Mt. Saishiteng is sufficient and comparable to that of the 4 m Daniel K. Inoue Solar Telescope (DKIST) at Haleakala, Hawaii (Özişik & Ak 2004). The median Fried parameter r_0 at Daocheng, Sichuan is 7.2 cm (Song et al. 2018).

During the initial phase in 2018, site testing equipment was transported to Mt. Saishiteng by helicopter, and we had to climb on foot to install and adjust the instruments. Since then, an asphalt road, internet, and electricity grid have reached Mt. Saishiteng. Considering the site testing results along with accommodation and logistics conditions at all candidate sites, Mt. Saishiteng was selected as the AIMS site. The actual AIMS dome location was chosen at a new hilltop at 4090 m altitude (38°34 26 N, 93°53 45 E), about 900 m south of the original site to avoid possible sunshine blockage from an eastern ridge during summer sunrise. By the end of 2021, AIMS dome construction was completed; Figure 18 shows a wide-angle view of the AIMS dome on Mt. Saishiteng taken on August 8, 2022.

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Note: Figure translations are in progress. See original paper for figures.