Solar Observation with the Fourier Transform Spectrometer. II. Preliminary Results of Solar Spectrum near the CO 4.66 m and Mg i 12.32 m Postprint

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Abstract

An infrared solar spectrum observed by ground-based telescopes is seriously affected by the background radiation both from the telescope and sky, relative to the visible wavelengths. Its accuracy is also influenced by the spectral resolution of the Fourier transform spectrometer. In the paper, we developed a CO2 gas cell and installed it in the sample compartment to calibrate the spectral resolution of the Bruker IFS-125HR at infrared wavelengths. The measured spectral resolution is 0.00342 ± 0.00086 cm−1 and 0.0059 ± 0.00024 cm−1 at the wavenumbers of 798 cm−1and 2136 cm−1, respectively. We also updated a fully reflective sunlight feeding system to observe the solar spectrum near CO 4.66 m and Mg i 12.32 m. By quickly pointing the sunlight feeding system about 1 degree away from the solar disk center, we are able to measure the background radiation from the telescope and the sky at Huairou Solar Observing Station. After removing the background radiation, our observed solar spectrum at CO 4.66 m is consistent with that from the National Solar Observatory. The Mg i 12.32 m working line selected by the Accurate Infrared Magnetic Field Measurements of the Sun (AIMS) project is also identified. Our method is helpful not only for the spectral resolution calibration and background radiation correction of AIMS but also for other infrared astronomical telescopes.

Full Text

Preamble

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Solar Observation with the Fourier Transform Spectrometer. II. Preliminary Results of Solar Spectrum near the CO 4.66 m and Mg I 12.32 m

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Abstract

Infrared solar spectra observed by ground-based telescopes are seriously affected by background radiation from both the telescope and sky compared to visible wavelengths. The accuracy is also influenced by the spectral resolution of the Fourier transform spectrometer (FTS). In this paper, we developed a CO_2 gas cell and installed it in the sample compartment to calibrate the spectral resolution of the Bruker IFS-125HR at infrared wavelengths. The measured spectral resolution is 0.00342 ± 0.00086 cm^{-1} and 0.0059 ± 0.00024 cm^{-1} at wavenumbers of 798 cm^{-1} and 2136 cm^{-1}, respectively. We also updated a fully reflective sunlight feeding system to observe the solar spectrum near CO 4.66 m and Mg I 12.32 m. By quickly pointing the sunlight feeding system about one degree away from the solar disk center, we are able to measure the background radiation from the telescope and sky at Huairou Solar Observing Station. After removing the background radiation, our observed solar spectrum at CO 4.66 m is consistent with that from the National Solar Observatory. The Mg I 12.32 m working line selected by the Accurate Infrared Magnetic Field Measurements of the Sun (AIMS) project is also identified. Our method is helpful not only for the spectral resolution calibration and background radiation correction of AIMS but also for other infrared astronomical telescopes.

Key words: Sun: infrared – methods: observational – instrumentation: interferometers

1. Introduction

With the rapid development of infrared detection technology and urgent scientific requirements, most new-generation solar telescopes are equipped with infrared post-focus instruments (Penn 2014). Recently, the solar spectrum near CO 4.66 m has gained extensive attention due to its unique role in probing the chromosphere, such as cold bubbles in the low solar chromosphere (Ayres 2003; Penn et al. 2011; Loukitcheva et al. 2019; Li et al. 2020; Song et al. 2023). Both the 4 m Daniel K. Inouye Solar Telescope (DKIST) and the 1.6 m Goode Solar Telescope (GST) are equipped with fully cryogenic instruments to cover the CO lines and have the ability to obtain observations with subarcsecond spatial resolution thanks to their large apertures (Cao et al. 2010; Fehlmann et al. 2016; Rimmele et al. 2020; Yang et al. 2020). Regarding longer wavelengths, DKIST is designed to cover wavelengths as far as 28 m (Rimmele et al. 2014). The Accurate Infrared Magnetic Field Measurements of the Sun (AIMS), which is the first mid-infrared astronomical telescope in China and will obtain its first light in 2023, is designed to observe the solar spectrum from 10 to 13 m. The Mg I 12.32 m line is selected as its main working line to accurately measure the solar magnetic field thanks to its high magnetic field sensitivity (Deng et al. 2016). Meanwhile, AIMS also incorporates a broadband imager at 8–10 m.

A Fourier transform spectrometer (FTS) is generally employed to realize high-resolution spectroscopic observations in the mid-infrared. For example, the ground-based McMath-Pierce Solar Telescope (MPST) administered by the National Solar Observatory in the United States (Brault 1972, 1978; Chang & Noyes 1983), the spaceborne Atmospheric Trace Molecule Spectroscopy (ATMOS) onboard Spacelab 3, and the Atmospheric Chemistry Experiment (ACE) onboard the Canadian SCISAT-1 satellite all rely on an FTS to observe the solar spectrum in the near- and mid-infrared wavelengths (Farmer et al. 1989; Farmer 1994; Hase et al. 2010). The FTS in these telescopes observes a point on the solar disk in a single observation since the detector has a single pixel. To cover the two-dimensional solar disk region, scanning in two orthogonal directions is required, resulting in low cadence or temporal resolution. To increase the temporal resolution, the FTS of AIMS has a 64 × 2 array detector.

Unlike visible observations, infrared solar observation with an FTS is seriously influenced by background radiation from both the telescope and Earth's atmosphere, especially for the mid- and far-infrared regions. The peak emission of a blackbody near room temperature (293 K) is about 9.8 m according to Wien's displacement law ($\lambda = b/T$, where $b = 2.897771955 \times 10^{-3}$ m $\cdot$ K and T is the temperature). As the opacity of the Earth's atmosphere or the temperature of the telescope varies, the background radiation also changes during observation, making correction necessary to increase the signal-to-noise ratio (S/N) of the data. Reducing the working temperature of the telescope, placing the telescope at high altitudes on Earth with low humidity or in a space orbit with a stable thermal environment, and employing the chopping and nodding technique during observation are three main methods to reduce variations in background radiation for nighttime mid-infrared telescopes (Papoular 1983; Glass 1999; Ohsawa et al. 2018; Rieke & Wright 2022). For solar observation, instrumental background radiation will vary faster due to the large heating flux from sunlight. Hence, the background radiation should be measured and corrected when observing the mid-infrared solar spectrum with an FTS.

Up to now, no astronomical telescope in China has used an FTS. More work must be done to obtain an accurate solar spectrum and further derive physical parameters. Bai et al. (2021) built an experimental system consisting of a Newtonian telescope, an optical fiber, and a newly installed FTS (Bruker IFS-125HR) at Huairou Solar Observing Station (HSOS). An inversion algorithm was developed and finally a solar spectrum at 0.4–2.2 m was obtained from the original interferograms taken by the FTS. Due to limitations imposed by the transmitted wavelengths in the optical fiber, mid-infrared solar observation near Mg I 12.32 m and CO 4.66 m could not be performed. Consequently, the method to measure and correct the background radiation could not be developed. Additionally, the instrumental width of the FTS was not calibrated, which is one of the most important parameters for evaluating the performance of an FTS and is needed both in the operation of AIMS to ensure data quality and in the Stokes inversion of solar magnetic fields.

Keeping these questions in mind, we updated the experimental system and present new results in this paper. The method to calibrate the instrumental width of the FTS is described in Section 2. The obtained mid-infrared solar spectrum, the background spectrum, and the background-corrected spectrum with our proposed method near CO 4.66 m and Mg I 12.32 m are presented in Section 3, followed by the conclusion and future perspectives.

2. Calibration of the Instrumental Spectral Resolution of the Bruker IFS-125HR

2.1. Principle of the Calibration Method with a Gas Cell

A series of target spectral lines with line widths much narrower than the spectral resolution of the FTS is needed to measure its instrumental spectral resolution. CO_2 has many absorption lines near CO 4.66 m and Mg I 12.32 m (or at wavenumbers near 2145 and 811 cm^{-1}) (Hinkle et al. 2003). The line width of a spectral line is mainly determined by Doppler and pressure broadening. The line width of gas molecules in the case of pressure broadening can be calculated with the following approximate formula:

δ _{pres}   0.05P(T/296)$^{-0 \cdot 5}$ cm^{-1} atm^{-1}

where P and T indicate pressure and temperature, respectively. From this formula, a narrower line width can be realized with lower pressure. Meanwhile, the line width in the case of Doppler broadening can be derived with the equation:

δ _{dop} = ($_0$/c)√(2kTln2/M)

where M is the molecular weight and $_0$ is the wavenumber value of the target line. If the temperature of the gas is lower, the line width is narrower. Based on these equations, we can control the line width by injecting gas into a cell with specific temperature and pressure.

If the pressure P of the gas is 1.8×10^{-3} atm (or 180 Pa) and T is 295 K (typical temperature in our laboratory), the corresponding line width caused by pressure broadening is 0.00018 cm^{-1}. For CO_2, the molecular weight is 44 and the Doppler broadening δ _{dop} is 0.0037 cm^{-1} and 0.00138 cm^{-1} at wavenumbers 2136 cm^{-1} and 798 cm^{-1}, respectively. The line width considering both pressure and Doppler broadening becomes 0.00371 cm^{-1} and 0.00139 cm^{-1} at wavenumbers of 2136 cm^{-1} and 798 cm^{-1}, respectively.

Compared with pressure broadening, Doppler broadening dominates if the pressure is very low in the gas cell. For our Bruker IFS-125HR, its maximum optical path difference (OPD) is 258 cm, and the ideal spectral resolution is 0.0035 cm^{-1} if the triangular apodization function is employed. This value will be larger in the near-infrared and visible wavelengths due to greater influence of aberration. Therefore, the CO_2 gas cell can be used to calibrate the instrument resolution of our FTS because its line width is much less than that of the FTS. The instrument resolution δ _{ins} equals the measured line width of the CO_2 gas cell with the FTS.

2.2. Calibration Unit and Result

Figure 1 [Figure 1: see original paper] shows a schematic diagram of our calibration unit attached to the Bruker IFS-125HR FTS. We customized a CO_2 gas cell with pressure of 1.8×10^{-3} atm (or 180 Pa) and placed it into the sample compartment of the Bruker IFS-125HR. The length of the cell is 20 cm to achieve larger absorption depth of the observed lines. During calibration, we use the built-in glowbar to provide infrared continuum radiation. Moreover, the FTS is evacuated to 69.2 Pa to reduce the influence of molecules in the air. The OPD of the FTS is set to 258 cm.

The recorded interferogram is presented in Figure 2 Figure 2: see original paper. The inversion algorithm proposed by Bai et al. (2021) is employed to invert the spectrum. The inverted CO_2 spectrum in the gas cell from 600 to 2000 cm^{-1} is shown in Figure 2(b). We can see many CO_2 absorption lines in two wavenumber regions: one from 600 to 800 cm^{-1} and the other from 1200 to 2000 cm^{-1}.

Two spectral lines near 798 and 2136 cm^{-1}, which are close to our target solar Mg I 12.32 m (811 cm^{-1}) and CO 4.66 m (2142 cm^{-1}) lines, are used to evaluate the instrumental width. The inverted results (red line with asterisk symbols) are shown in Figure 3 [Figure 3: see original paper]. We apply a single Gaussian function (blue plus symbols) to fit the two lines. The fitted full width at half maximum (FWHM) is 0.0037 ± 0.0008 cm^{-1} at 798 cm^{-1} and 0.007 ± 0.00028 cm^{-1} at 2136 cm^{-1}. The fitting error mainly arises from the limited S/N of the inverted lines. Uncertainty in pressure and Doppler broadening also influences the instrumental width of an FTS. The error is 0.00018 cm^{-1} assuming the uncertainty of pressure in the gas cell is 180 Pa, which is the upper limit for a cell with a reasonable leaking rate.

The FTS and gas cell are arranged in the laboratory with temperature controlled at 295 ± 3 K. Errors from temperature uncertainty are 0.000134 cm^{-1} at wavenumbers of 798 cm^{-1} and 2136 cm^{-1}, respectively, even if we assume the temperature ranges from 285 K to 305 K. The corresponding instrumental widths are 0.00342 ± 0.00086 cm^{-1} and 0.0059 ± 0.00024 cm^{-1} at wavenumbers of 798 cm^{-1} and 2136 cm^{-1}, respectively, after considering the above-mentioned errors. The resolution at larger wavenumber (shorter wavelength) is worse due to more serious influence from optical aberrations and adjustment errors.

3. Measurement and Correction of the Background Radiation from the Observed Solar Spectrum

3.1. Brief Introduction of the Updated Sunlight Feeding Experimental System

The maximum wavenumber obtained by the sunlight feeding experimental system in Bai et al. (2021) is about 4545 cm^{-1}, with the remainder of the solar spectrum cut off by the optical fiber. Moreover, the collecting area of the telescope is small since the diameter of the primary mirror is only 10 cm. Therefore, we updated the sunlight feeding experimental system and present its optical diagram in Figure 4 [Figure 4: see original paper]. The main differences from Bai et al. (2021) are:

1. All optical elements are reflecting mirrors to cover a broad wavelength range from visible to mid-infrared.
2. We used an existing telescope at HSOS with a larger aperture of 60 cm to collect more photons. The original Cassegrain system was updated to a Gregorian system having two field stops (1 and 2 in Figure 4) with an effective focal length of 10 m. Sunlight from the Gregorian system is reflected to the vertical optical path by two plane mirrors (M3 and M4) and arrives at field stop 2. The convergent sunlight after field stop 2 is further collimated by an off-axis parabolic mirror (M5) with a focal length of 200 cm. With the assistance of two plane mirrors (M6 and M7), the collimated sunlight is converted from the vertical to the horizontal path. The horizontal path has an on-axis parabolic mirror (M9) with a focal length of 600 cm, field stop 3, an off-axis parabolic mirror (M10) with a focal length of 50 cm, and two plane mirrors (M8 and M11). After the final plane mirror M11, the collimated sunlight from a partial region of the Sun is fed into the Bruker IFS-125HR. The collimated sunlight is focused by an off-axis parabolic mirror with a focal length of 41.8 cm inside the Bruker IFS-125HR. The effective focal length of the sunlight feeding system at the focus of Bruker IFS-125HR is about 25.2 m. The field of view observed by the FTS is selected by rotating the field stop wheels of different apertures.

3. The Gregorian telescope (M1–M3) is mounted on an equatorial platform that can point at and track the Sun. We can also point the telescope to the sky near the Sun within several seconds to record background radiation from both the Earth's atmosphere and the telescope itself.

All field stops used in the experimental system are not cooled so far.

3.2. The Solar Spectrum and Background Radiation near 12.32 m

We carried out solar spectral observation with the newly updated sunlight feeding experimental system and the Bruker IFS-125HR at 04:49 UT on 2021 March 20. A KBr beam splitter was selected to transmit mid-infrared radiation, which was received by a HgCdTe detector cooled by liquid nitrogen. Only the detector worked at low temperature during the observation. It is well known that infrared observation is seriously influenced by background radiation from both the Earth's atmosphere and the telescope. To remove the background radiation, we take two measurement steps. First, an interferogram I_{igm} is taken by pointing the telescope to a quiet Sun region near the center of the solar disk. Second, a background interferogram I_{igm}^{bgd} is obtained by pointing the telescope to a clear sky region about one degree away from the disk center.

The original observed I_{igm} (blue curve) and I_{igm}^{bgd} (green curve) are shown in Figure 5 Figure 5: see original paper. Figure 5(b) shows the zoomed-in region with OPD from -0.06 to 0.06 cm. The background radiation is clearly visible. The quasi-periodic pattern in the interferogram is generated by the narrowband filter. The transmitted wavenumber range of the FTS is very broad, and shot noise from the broadband radiation is included at each point of the interferogram. If a narrowband filter is adopted, shot noise outside the target waveband will be reduced and the S/N of the solar spectrum will be higher. The Gaussian-type large-scale curve in the interferogram is caused by absorption lines from both the solar and Earth's atmospheres. Figure 5(c) displays the inverted solar spectrum I (blue) and the background spectrum I_{bgd} (green) using the inversion algorithm from Bai et al. (2021). Unlike the original solar spectrum, the background spectrum has only a continuum component and shows no absorption lines due to its low resolution. This result is reasonable because our target is the cold Earth sky and the formation mechanism is blackbody continuous radiation. The ratio of original solar to background radiation also depends on wavenumber.

Once the original solar spectrum I and background radiation I_{bgd} are known, we can obtain the real solar spectrum with the equation I_{Sun} = I - I_{bgd}. Figure 6 [Figure 6: see original paper] presents the three curves of I, I_{bgd}, and I_{Sun} near 12.3 m in black, blue, and red, respectively. The emission line near 811.6 cm^{-1} is Mg I 12.32 m, the target line of AIMS, which is first observed here in the Chinese solar community. The two nearby absorption lines originate from CO$_2$ molecules in the Earth's atmosphere and can be used for monitoring the long-term stability of the FTS as well as executing wavelength calibration to produce high-level scientific data from AIMS.

The FWHM of the background-corrected Mg I 12.32 m line is about 0.0086 ± 0.0019 cm^{-1} (including the FTS instrumental profile), while it is about 0.017 cm^{-1} in Brault's observation (Brault & Noyes 1983). For the continuum region, the value of the original I is about 0.24 and the background radiation is about 0.045. The original solar radiation is 5.33 times that of the background. As only the detector is cooled in our experimental system, thermal radiation from the field stops and optical elements also contributes to the background radiation. HSOS has an elevation of 60 m and is near a reservoir, so the influence of water vapor is also high. All these factors result in substantial background radiation. AIMS will be installed at Lenghu Station with an elevation of 4000 m, and since the telescope will have cryogenic detectors as well as optical elements, the background radiation should be much less than in our observation. Furthermore, the S/N of the original and background-corrected spectrum is 35.1 and 29.67, respectively. As the background radiation is taken with very low resolution and has high S/N, the S/N remains almost the same during the background correction process.

3.3. The Solar Spectrum and Background Radiation near 4.66 m

We also installed a narrowband filter centered near 2150 cm^{-1} (4.65 m) with a width of 80 cm^{-1} to observe the solar spectrum near 4.66 m at 07:08 UT on the same day. Similar to the observation near 12.3 m, two interferograms (I_{igm} and I_{igm}^{bgd}) were taken and are shown in Figure 7 Figure 7: see original paper. The OPD of I_{igm} ranges from −10 cm to 90 cm, indicating a spectral resolution of 0.01 cm^{-1}. The OPD interval is 1.898 m and wavelengths larger than 3.8 m can be reconstructed. Acquiring all data points in I_{igm} takes 13.2 s with 40,000 interference points sampled per second. The OPD of the background interferogram I_{igm}^{bgd} is taken from −9 to 9 cm with a resolution of 0.1 cm^{-1} to increase the S/N of the inverted background spectrum. Figure 7(b) shows the zoomed-in interferograms of I_{igm} (blue) and I_{igm}^{bgd} (green). The corresponding inverted spectra I and I_{bgd} are displayed in Figure 7(c). Many absorption lines exist in the waveband, and the background radiation is very weak near 4.6 m.

The background-corrected spectrum I_{Sun} and the background radiation I_{bgd} near CO 4.667 m are depicted in Figure 8 [Figure 8: see original paper]. The CO lines studied in Li et al. (2020), Song et al. (2023), and Uitenbroek et al. (1994) are identified. Both I_{Sun} and I_{bgd} are normalized with the continuum of I_{Sun}. The background radiation is about 0.006, meaning that the solar radiation is 166.6 times that of the background. The ratio between background and solar radiation at CO 4.66 m is much larger than the value at Mg I 12.32 m. This result is reasonable since radiation at shorter wavelengths is less influenced by thermal background. The S/N is 77.2 after correcting the background spectrum. We also overplot the solar spectrum (green line) taken by the FTS at Kitt Peak Observatory (Livingston & Wallace 1991). The two curves are consistent with each other, indicating the effectiveness of our FTS configuration, inversion algorithm from interferogram to spectrum, and background correction method. The disparity near 2142.3 cm^{-1} is caused by different absorptions from the Earth's atmosphere.

4. Conclusion and Future Perspective

We developed a fully reflective sunlight feeding system and successfully observed a high-resolution infrared solar spectrum longer than 2.5 μm with the Bruker IFS-125HR, a first for the Chinese astronomical community. The main results from the new observing system are summarized as follows:

1. We introduced the principle of the inversion algorithm from interferogram to spectrum as well as the background radiation correction method. The spectral resolution calibration method with a gas cell working at low pressure was described. With the gas cell, the spectral resolution of the Bruker IFS-125HR was measured to be 0.00342 ± 0.00086 cm^{-1} and 0.0059 ± 0.00024 cm^{-1} at wavenumbers of 798 cm^{-1} and 2136 cm^{-1}, respectively.
2. The infrared background radiation is measured by quickly pointing the telescope to the sky nearby after the solar spectrum is taken. The ratio of the original solar spectrum to background radiation on 2021 March 20 at HSOS is about 166.6 and 5.33 at 2142 cm^{-1} and 811 cm^{-1}, respectively. The background radiation can be effectively removed in the inverted solar spectrum. We suggest using a low-resolution background spectrum by setting a smaller OPD of the FTS to correct the original solar spectrum, as the S/N of this low-resolution background spectrum is higher, resulting in better S/N of the solar spectrum after background correction.
3. We identified the Mg I 12.32 μm line in the background-corrected quiet Sun spectrum. The OPD of the interferogram in the FTS was set to 180 cm, which is larger than the 100 cm used in Brault & Noyes (1983). The line width is about 0.0086 ± 0.0019 cm^{-1}, which is narrower than the value of 0.017 cm^{-1} from Brault & Noyes (1983).
4. We also identified the CO 4.66 μm lines in the background-corrected quiet Sun spectrum. The OPD is configured almost the same as the data from Livingston & Wallace (1991)'s atlas. The background-corrected CO lines agree well with the atlas data, verifying our spectral observation with the Bruker IFS-125HR.

The sunlight feeding system and the Bruker IFS-125HR provide a valuable platform both for the development of new infrared technologies and for scientific studies of the broadband solar spectrum at 0.4–25 μm. With this platform, we carried out solar spectral observation with the Bruker IFS-125HR equipped with a fast-readout CMOS detector in the visible band (Zhu et al. 2022). Tens of thousands of wavelength interferograms with 20 × 80 pixels were obtained within less than one minute. After inversion, the data cube is derived with a two-dimensional image and a one-dimensional spectrum. Compared with a point-source detector used here and a 64 × 2 detector used by AIMS, solar spectral observation with a two-dimensional detector can make full use of the advantages of the FTS (Stenflo 2017) and significantly increase its temporal resolution. More work will focus on two-dimensional solar FTS observation in the future thanks to the rapid development of detectors with fast readout speed and low noise.

The platform also provides a good reference for instrumental calibration, observing mode design, and scientific data processing of the AIMS telescope. The data quality of AIMS will be influenced by the instrumental width (spectral resolution) of the FTS, the background radiation, and the S/N of the spectrum after background correction. Our work demonstrates that a gas cell with low pressure and suitable temperature is a convenient way to calibrate and monitor spectral resolution variations of AIMS. The sunlight can provide the background radiation used for generating absorption lines to derive the FWHM of an FTS. The gas cell is inserted into the light path of AIMS during the calibration process and shifted out after calibration. The telescope for AIMS should be quickly pointed away from the solar disk to measure the background radiation from both the instrument and Earth's sky. The background radiation also needs to be measured with a certain cadence to monitor its variation.

Regarding the S/N, which determines the magnetic field sensitivity of AIMS, several methods are helpful. An FTS has the advantage of broadband spectral observation, but the S/N is too low for a single wavelength point, especially for the first observation with high spectral resolution. Hence, one method is to employ a narrowband filter to reduce photon noise from other wavelength ranges. We also suggest using moderate spectral resolution (e.g., 0.01 cm^{-1}) for AIMS's routine observation. Both the S/N and temporal resolution will be increased then. Third, the spectral resolution of the background radiation measurement influences the S/N. As the background radiation is weaker than the solar spectrum, low spectral resolution is needed to increase the S/N. Multiframe superposition also helps improve S/N. In summary, AIMS's observing mode for background radiation measurement should have the ability to quickly point to the solar disk, take observations with low spectral resolution, and perform multiframe integrations. In addition, the FTS of AIMS has a detector with 64 × 2 pixels. The central wavelength is different for each pixel. The two CO_2 telluric lines near the Mg I 12.32 m working line shown in Figure 6 provide a good reference for accurate wavelength calibration.

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