Accurate Group Delay Measurement for Radial Velocity Instruments Using the Dispersed Fixed Delay Interferometer Method. II. Application of Heterodyne Combs Using an External Interferometer Filter

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ABSTRACT. A fixed delay interferometer is the key component in a DFDI (dispersed fixed delay interferometer) instrument for an exoplanet search using the radial velocity (RV) technique. Although the group delay (GD) of the interferometer can be measured with white light combs (WLCs), the measurement precision is limited by the comb visibility, and the wavelength coverage is constrained by the comb sampling. For instance, this method can calibrate only half of the SDSS-III MARVELS spectra and reach a precision of 2 m s\(^{-1}\). This article introduces an innovative method using a sine source for precision delay calibration over very broad wavelengths. The sine source is made of a monolithic Michelson interferometer fed with white light. The interferometer modulated white light (in a sinusoidal form) is fed into a DFDI instrument for calibration. Due to an optimal GD of the sine source, Fourier components from the DFDI interferometer, the sine source, and their frequency beating can be clearly separated and effectively extracted with a chirped Fourier transform to allow precision measurements of the interferometer GD over the entire range of operation wavelengths. The measurements of the MARVELS interferometer with a sine source show that this new calibration method has improved the wavelength coverage by a factor of 2 and the precision by a factor of 3. The RV measurement error induced by GD measurement uncertainties is controlled to be less than 1 m s\(^{-1}\), which has met the requirements for MARVELS moderate-to-high Doppler precision (\(\sim 5–30\) m s\(^{-1}\)) for exoplanet search around \(V \sim 8–12\) solar-type stars. Heterodyne combs using an external interferometer source can be applied in other areas of optics measurement and calibration.

Online material: color figures

1. INTRODUCTION

The past two decades have seen a tremendous advancement in our knowledge of exoplanet systems. More than 700 exoplanets have been detected by the radial velocity (RV) technique,\(^1\) which is one of the most successful detection methods in exoplanet search and characterization. The RV technique uses a host star’s Doppler signal, induced by the reflex motion of an unseen orbiting planet. Traditionally, the Doppler signal is measured by monitoring tiny shifts of centroids of stellar absorption lines with a high-resolution spectrograph (Mayor & Queloz 1995; Butler et al. 1996). RV precision of 1 m s\(^{-1}\) has been achieved routinely (Bouchy et al. 2009; Howard et al. 2010) with spectrographs such as High Accuracy Radial Velocity Planet Searcher (HARPS) (Mayor et al. 2003) and High Resolution Echelle Spectrometer (HIRES) (Vogt et al. 1994). It is more difficult to measure Doppler signal with a spectrograph at lower spectral resolution because stellar lines are less resolved due to a more blurred instrument profile. An innovative idea—the dispersed fixed-delay interferometer (DFDI) method—was introduced and developed (Erskine & Ge 2000; Ge 2002; Ge et al. 2002). This method combines an interferometer and a low-to-medium resolution spectrograph in a precision RV measurement. In comparison to the traditional RV technique, the DFDI method can achieve similar measurement precision at a lower spectral resolution (Erskine & Ge 2000; Ge 2002; Ge et al. 2002; van Eyken et al. 2010; Wang et al. 2011). At low-to-medium resolutions, a fixed detector space can include more stellar spectra, which opens up the field for a multi-object exoplanet survey.

MARVELS (Multi-object Apache Point Observatory Radial Velocity Exoplanet Large-area Survey) is part of the Sloan Digital Sky Survey (SDSS) III (Gunn et al. 2006; Eisenstein et al. 2011). The instrument is capable of simultaneously monitoring RVs of 60 stars and will provide sufficient measurement precision for exoplanet detection (Ge et al. 2009). MARVELS has demonstrated its potential to reveal low-mass companions around other stars (Fleming et al. 2010; Lee et al. 2011; Wisniewski et al. 2012). It covers a wavelength range from 500 to 570 nm and uses a post-dispersive grating with a spectral resolution of 11,000 after a fixed delay interferometer. In the

\(^1\) See http://exoplanet.eu/; http://exoplanets.org/.
DFDI method, a fixed delay interferometer (Wan et al. 2009, 2011) plays a crucial role in creating stellar spectral fringes whose phases are used for high precision RV measurements (Ge 2002; Erskine 2003). The group delay (GD) of the fixed delay interferometer determines the scale that translates phase change into RV shift. GD is defined by the following equation:

$$GD(\nu) = -\frac{1}{2\pi} \frac{d\phi}{d\nu}, \quad (1)$$

where $\phi$ is phase shift, and $\nu$ is optical frequency. In the case of an interferometer, can be described by the following equation:

$$\phi(\nu) = \frac{2\pi\tau(\nu)\nu}{c}, \quad (2)$$

where $\tau$ is the optical path difference (OPD) of the interferometer and $c$ is the speed of light. The OPD of an interferometer is determined by the thicknesses ($l$) and refraction indices ($n$) of the two arms. In the case of a monolithic interferometer, where two pieces of second surface mirror are used as arms, the OPD can be calculated as:

$$\tau(\nu) = n_1(\nu)l_1 - n_2(\nu)l_2, \quad (3)$$

where the subscripts represent different arms. The interferometer for MARVELS is designed to be field compensated to minimize the influence of input beam instability (Wan et al. 2009; Wang et al. 2010). To ensure field compensation, the thicknesses and materials are chosen such that the virtual images of the two arms overlap. Because glasses are used in the optical paths, $\phi$ no longer changes linearly with frequency, so GD is dependent on the optical frequency. An inaccurate GD measurement may significantly limit the RV measurement accuracy (Barker & Schuler 1974; van Eyken et al. 2010).

Wang et al. (2012a) introduced two methods of GD measurement. One method uses a known RV reference star to calibrate GD, and the other uses the white light combs (WLCs) generated by the interferometer to measure GD. While both methods can provide an adequately accurate GD measurement for RV planet survey, the WLC method is more fundamental and does not require additional observation for GD calibration. However, several challenges prevented us from obtaining a satisfactory result. First of all, the visibility of WLCs is very low because of limited spectral resolution and pixel sampling rate. Secondly, the GD of the MARVELS interferometer is large enough that the phase jump between pixels at the high end of the frequency coverage exceeds $\pi$ which caused failure in phase unwrapping.

In this article, we will introduce an innovative method of GD measurement using heterodyne combs created by the beat of two interferometers. By using an external interferometer, which creates beat signals with the MARVELS interferometer, both challenges mentioned above can be overcome. We will show that the new result leads to a more precise GD measurement over a wider frequency coverage. Methodologies will be introduced in § 2 and results will be reported in § 3. In § 4, we will summarize and discuss the new method and its implications for future works.

2. METHODOLOGIES

2.1. An External Sine Source

A sine source is a field- and thermally-compensated monolithic Michelson interferometer (Wan & Ge 2010; Wang et al. 2012b). When it is fed with a white light source, the output spectral form resembles a sinusoidal wave. This type of interferometer is therefore named a source. The sine source is designed to be insensitive to ambient temperature change and incident beam instability. When it is situated in a temperature-controlled and mechanically-stabilized structure, the sine source output spectrum is extremely stable, making it an ideal wavelength calibration source in both the optical and NIR wavelengths. We applied the sine source as an external interferometer filter for the MARVELS interferometer GD measurement. The heterodyne combs, created by the frequency beat between the sine source and the MARVELS interferometer, help to recover the WLC signals from the MARVELS interferometer. GD is then determined from the phase measurement for the WLC signals and the wavelength solution from a Th-Ar emission lamp.

2.2. Frequency Chirp

A chirp is a signal whose spatial frequency increases or decreases with optical frequency. The signal can be described by the following equation:

$$I(\nu) = \frac{1}{2} (1 + \gamma(\nu) \cos(\phi(\nu))), \quad (4)$$

where $\nu$ is optical frequency; $\gamma$ is visibility, defined as the ratio between half of the peak-valley amplitude and the DC offset; and $\phi$ is phase, which is defined by equation (2). The OPD of an interferometer is determined by the thicknesses ($l$) and refraction indices ($n$) of the two arms. In the case of a monolithic interferometer in which two pieces of second surface mirror are used as arms, the OPD can be calculated using equation (3). Within a relatively small bandwidth ($\Delta\nu \leq 100$ THz), $\tau$ can be approximated as a linear function of $\nu$. This linear approximation will facilitate the data analysis process, particularly for chirp Fourier transform (Xia 1999), described later in this article (§ 2.4).

2.3. Frequency Beat

A beat is the interference between two signals with different spatial frequencies:
\[ I(\nu) = I_1(\nu)I_2(\nu) \]
\[ = \frac{1}{4} \left(1 + \gamma_1 \cos \phi_1 + \gamma_2 \cos \phi_2 + \gamma_1 \gamma_2 \cos \phi_1 \cos \phi_2\right) \]
\[ = \frac{1}{4} \left(1 + \gamma_1 \cos \phi_1 + \gamma_2 \cos \phi_2 + \frac{1}{2} \gamma_1 \gamma_2 \cos(\phi_1 - \phi_2)\right) \]
\[ + \frac{1}{2} \gamma_1 \gamma_2 \cos(\phi_1 + \phi_2) \].

(5)

where \(\nu\) dependence is omitted in the equation, \(I_1\) depicts the MARVELS interferometer signal, and \(I_2\) depicts the external sine source signal. \(I_1\) has a higher spatial frequency than \(I_2\). The five components in equation (5) can be separated in Fourier domain, if they are not overlapped and the sampling rate is high enough. In our study, the last component of the signal is washed out because of the finite sampling rate. Therefore, equation (5) can be rewritten as:

\[ I(\nu) = \frac{1}{4} \left(1 + \gamma_1 \cos \phi_1 + \gamma_2 \cos \phi_2 + \frac{1}{2} \gamma_1 \gamma_2 \cos(\phi_1 - \phi_2)\right) \]
\[ = \frac{1}{4} \left(1 + \gamma_1 \cos \left(\frac{2\pi \tau_1 \nu}{c}\right) + \gamma_2 \cos \left(\frac{2\pi \tau_2 \nu}{c}\right)\right) \]
\[ + \frac{1}{2} \gamma_1 \gamma_2 \cos \left(\frac{2\pi(\tau_1 - \tau_2) \nu}{c}\right) \].

(6)

In our previous article, we only were able to measure the GD for half of the spectrum because the spatial frequency at one end had already exceeded the Nyquist sampling rate, which resulted in failure in phase unwrapping (Wang et al. 2012a). In this article, we connect the sine source (smaller OPD) in sequence with the MARVELS interferometer (larger OPD) in order to generate a beat signal, as described in equations (5) and (6). Figure 1 shows the WLC signal and visibility measurement results. The visibility and effective signal-to-noise ratio (S/N) are significantly improved over those of the previous WLCs signal generated by the MARVELS interferometer alone. The phase for the MARVELS interferometer (\(\phi_1\)) is measured indirectly by summing the phase measurement results of two components with lower spatial frequency, i.e., the sine source component \([1/4\gamma_2 \cos \phi_2]\) and the beat component \([1/8\gamma_1 \gamma_2 \cos(\phi_1 - \phi_2)]\).

### 2.4. Phase Measurement Using the Discrete Chirp-Fourier Transform

Phase measurement of these two low frequency components is only possible when they can be well separated in Fourier domain. We have made efforts both in hardware design and in data analysis to ensure that the above conditions are met. First of all, the OPD of the MARVELS interferometer is approximately 7 mm. The external sine source is designed with an OPD of \(\sim 4.5\) mm; the beating OPD, which is the OPD difference between the two interferometers, is thus \(\sim 2.5\) mm. A larger OPD would result in crosstalk with the high frequency component generated by the MARVELS interferometer, and a smaller OPD would result in crosstalk with the beat signal. Figure 2 shows the power spectrum of the WLCs signal (Fig. 1) based on discrete Fourier transform. Two broad peaks, which correspond to the beat signal and the sine source signal, can be seen. The peak is broadened because of glass dispersion, as discussed in \$2.2. Two these peaks are visibly separated, but overlap of them also is clear in the region around 0.2 cycle/pixel. Secondly, we apply discrete chirp-Fourier transform (Xia 1999) to increase the power and reduce the width by selecting an appropriate chirp rate that maximizes the power of a specific component. The crosstalk between different components in equation (6) is therefore reduced significantly. Figure 3 shows the windowed power spectrum based on discrete chirp-Fourier transform. Not only are the two peaks (red and blue peaks in Fig. 3) in Figure 2 clearly separated, but the peak (green peak) corresponding to the MARVELS interferometer signal also becomes visible. Phase of a component is measured by selecting...
a window that encompasses the corresponding power peak in the positive frequency domain and then calculating the argument of the inverse discrete chirp-Fourier transform using the same chirp rate. We verify that the phase measurement is insensitive to window size, unless it covers another peak. Measured phase is then unwrapped to remove $2\pi$ ambiguity.

3. EXPERIMENTAL SETUP AND RESULTS

3.1. Experimental Setup

The MARVELS instrument covers a wavelength range from 500 to 570 nm. A post-dispersive grating with a spectral resolution of 11,000 is used after a fixed delay interferometer (Ge et al. 2009). Phase and frequency are measured in the experiment in order to calculate GD according to its definition (eq. [1]). Similar to previous GD measurement experiments (Kovács et al. 1995; Amotchkina et al. 2009), white light is input into an interferometric system and then dispersed by a spectrograph. There are two key differences between previous experiments and the experiment with the MARVELS instrument: (1) Phase is independently measured in each frequency channel in Amotchkina et al. (2009) by phase stepping, while it is measured in this experiment using the discrete chirp-Fourier transform technique, as described in § 2.4. (2) An external interferometer is added to the optical system in order to increase fringe visibility and separate different Fourier components. A Th-Ar emission lamp is used as a wavelength calibration source. The top view and side view of the experimental setup are shown in Figure 4. An external sine source is connected sequentially to the MARVELS system with fiber optics and placed upstream of 60 fibers. According to Wang et al. (2012a), each fiber creates two spectra, one picked from the forwarding beam and one from the returning beam (see Fig. 4). A total of 120 spectra allow us to measure GDs at 60 positions on the interferometer along the vertical (slit) direction. There are 24 pixels along the slit direction for each spectrum. We chose 15 rows in the middle to measure GD because of relatively higher photon flux. The GD for a particular fiber number is obtained by averaging the results of the GD measurements for those rows associated with the fiber.

3.2. Results

Figure 5 shows the phase measurement results for the different components in equation (6). Red is the phase for the beat signal between the two interferometers, blue is the phase for the sine source, and green is the phase for the MARVELS interferometer. The phase measurement for the MARVELS interferometer fails in the optical frequency region between 575 and 595 THz because of a phase jump of more than $2\pi$, which is problematic for phase unwrapping. In regions with a relatively lower optical frequency between 535 and 575 THz, phase measurement results are self-consistent because the sum of the beat phase and the sine source phase is equal to the phase of the MARVELS interferometer. The top panel of Figure 6 shows phase measurement results for the center row as a function of frequency at different fiber numbers. The phase fitting residual with a third-order polynomial (shown on the bottom panel of Fig. 6, rms = 0.3 rad) is roughly consistent with photon-noise limited measurement error (see § 4.3 for details).
Figure 7 shows the GD measurement results at $\nu = 550$ THz as a function of fiber number. Note that the two arms of the MARVELS interferometer are intentionally tilted toward each other, and the 60 fibers are mounted evenly along the slit direction. The measured GDs should vary gradually with fiber number. We use a second-order polynomial to fit the GD variation with fiber number. The fitting residual has an rms of 0.0022 ps. Figure 8 shows the fitted GD as a function of frequency for different fibers. GD varies 0.40 ps (1.6%) across a measurement range from 530 to 595 THz. Ignoring the GD dependence of frequency would result in a $480 \text{ ms}/C_0$ measurement offset between the two ends of the measurement range (assuming a true RV of $30,000 \text{ ms}/C_0$, which is a typical stellar RV value due to the Earth’s barycentric motion). Table 1 provides the polynomial fitting coefficients of GD versus fiber number at different frequencies within the measurement range.

3.3. Comparison to Previous Works

Wang et al. (2012a) used the WLCs generated by the MARVELS interferometer to measure the GD of the interferometer. GD can be measured over only half of the frequency coverage because of low visibility and poor pixel sampling rate. By adding an external sine source upstream of the MARVELS interferometer, a beat signal is created, which dramatically increases visibility and thus the effective S/N. By measuring the phase of the beat signal and the phase of the sine source, the phase of the MARVELS interferometer can be determined over the entire frequency coverage. The GD of the MARVELS interferometer can therefore be measured together with frequency calibration.
information, which is provided by a Th-Ar emission lamp. Figure 8 shows both the previous GD measurement results (Wang et al. 2012a) and the results from this work. They are consistent with each other within reported measurement errors. In summary, the GD measurement results of the MARVELS interferometer has shown an improvement in precision by a factor of $\sim 3$ and an improvement in measurement range by a factor of $\sim 2$. A more detailed comparison can be found in Table 2.

### Table 2

**Comparison between Wang et al. (2012a) and This Work**

| Spectral coverage  | Half  | Full  |
|--------------------|-------|-------|
| S/N                | $\sim 15$ | 30–80 |
| Current precision  | $\sim 6.6 \times 10^{-3}$ ps | $\sim 2.3 \times 10^{-3}$ ps |
| Current RV error$^1$ | 2.2 ms$^{-1}$ | 0.9 ms$^{-1}$ |
| Dependence on pipeline | $\sqrt{\cdot}$ | $\sqrt{\cdot}$ |

$^1$ RV error is calculated assuming a true velocity shift ($\Delta v$) of 10,000 m s$^{-1}$, according to equation (7).

### 4. Summary and Discussion

#### 4.1. Summary

We overcome the low visibility and high spatial frequency of WLCs generated by the MARVELS interferometer by modifying the previous experimental scheme (Wang et al. 2012a). We introduce an innovative method that makes use of the beat of two interferometers (an external sine source and the MARVELS interferometer) in order to increase visibility. The phase of the MARVELS interferometer can therefore be measured at a higher effective S/N and broader frequency coverage. Discrete chirp-Fourier transform is introduced to the data analysis to minimize crosstalk between different signal components. We are able to improve the previously reported measurement range by a factor of $\sim 2$ and the precision by a factor of $\sim 3$. A more precisely measured GD would introduce less RV measurement uncertainty and thus facilitates exoplanet detection. The application of heterodyne combs created by the beat of two interferometers can be generalized to other areas of optics measurement and calibration.
4.2. GD Variation of the MARVELS Interferometer

The GD of a monolithic interferometer, like that of the MARVELS interferometer, which consists of a beam splitter and two second surface mirrors, changes with temperature and incident angle. Linear thermal sensitivity of the MARVELS interferometer is measured at $-2.6 \times 10^{-6} \, \text{K}^{-1}$ (Wan et al. 2011). The GD variation at 10 mK temperature fluctuation (typical temperature fluctuation scale for MARVELS instrument) would be $6.5 \times 10^{-6} \, \text{ps}$, which is well below measurement precision. Wan et al. (2011) reported that a phase change of $\pi/2$ is measured at an incident angle of $23.8^\circ$. Such a phase change corresponds to a $\sim 4 \times 10^{-4} \, \text{rad}$ change in the GD measurement. Again, this value is much lower than the measurement error reported in this article (see Table 1). Therefore, the GD variation due to temperature and incident angle change cannot be measured, given the current measurement precision.

4.3. GD Measurement Error Introduced by Data Pipeline

Similar to Wang et al. (2012a), we conduct a bootstrapping experiment to investigate the influence of phase measurement and wavelength calibration uncertainties on GD measurement uncertainty. The uncertainty of phase measurement is $\sim 0.24$ rad under the photon-noise limited condition, assuming a S/N of 120 and a typical fringe visibility of 15%. The uncertainty due to the wavelength calibration is $\sim 0.002$ THz (0.02 Å). A relative GD measurement error ($\delta GD/GD$) of $1.5 \times 10^{-5}$ is predicted at the current phase measurement and wavelength calibration uncertainty levels. In comparison, the median of the relative GD measurement error is $\sim 8 \times 10^{-5}$ for all considered frequencies (see Table 1). The suspected error contribution from the data pipeline (Wang et al. 2012a) may still be responsible for the discrepancy between the predicted and actual GD measurement uncertainties. The range of the unwrapped phase is $\sim 10,000$ rad, according to Figure 6. A relative GD error of $\delta \phi/10,000$ would result if a systematic phase error, $\delta \phi$, is introduced by the data pipeline when correcting for optical distortions. The systematic phase error can easily be on the order of several tenths of radians, considering the phase change is 2.5 rad between horizontal pixels and 0.6 rad for vertical pixels (Wang et al. 2012a). If different fibers are treated independently, which is the case for the MARVELS data reduction pipeline, then the discrepancy may possibly be explained. Therefore, a better handle of optical distortions, such as spectrum curvature and spectral line slant, is critical for improving GD measurement precision for future experiments.

4.4. RV Deviation Induced by GD Measurement Error

RV uncertainty introduced by GD measurement error can be described by equation (7) (Barker & Schuler 1974; Wang et al. 2012a):

$$ \delta v = \frac{\delta GD}{GD} \Delta v, $$

where $\delta v$ is the deviation of the RV measurement from the true value, $\delta GD/GD$ is the relative error for the GD measurement, and $\Delta v$ is the RV change. The typical range of RV variation is within $30,000 \, \text{m s}^{-1}$ for a precision RV measurement for an exoplanet search. This RV range is mainly due to the Earth’s barycentric motion. At the current measurement precision, which corresponds to $\sim 9 \times 10^{-5}$ relative error, a maximum RV deviation of $2.7 \, \text{m s}^{-1}$ would be induced.

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