The Novel Optical System of Measuring the Speed of Starlight

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Abstract: We proposed a novel method and implemented an optical system accordingly to measure the speed of starlight by using the well-known speed of light from a terrestrial source, *c*, as a metric basis. This system consists of a transmitter and a receiver. The transmitter modulated starlight, terrestrial red and infrared lights into pulses simultaneously. These pulses were detected by the distant receiver. A high speed oscilloscope is used to record the pulses arrival times, where the terrestrial infrared pulse and the red pulse are used as the trigger and the reference signals. During the measurement, we employed a terrestrial white light travelling along the exact path of the starlight to calibrate the system. We found that the starlight pulses arrived at the receiver with various degrees of delays, compared with that of the terrestrial white light pulse. The values of the delays are likely related to the relative radial velocities of the stars. The result implies that the measured apparent speed of starlight is not constant.

1 INTRODUCTION

The speed of light is an important physical paremeter which is used to estimate other physical parameters such as mass, time, space, energy, etc. In 1676, Römer investigated the eclipses of Io, Jupiter's nearest moon, and estimated that the speed of light was about 214,000 km/sec. In 1728, Bradley observed aberration of Draconi. He gave a value for the speed of light of 301,000 km/sec. Both measurements used light from extraterrestrial sources. In 1849, Fizeau used a chopper and a distant mirror to measure the speed of light on the terrestrial. He estimated the speed of light equal to 3.153×10^8 m/sec. In 1862, Foucault employed a rotating mirror instead of a chopper. He obtained a value of the speed of light about 298,000 km/sec ±500 km/sec. In 1878, Michelson constructed the famous Michelson interferometer to measure the effect of ether on the speed of light. He concluded that the hypothesis of stationary ether was incorrect. During 1880 and 1882, Michelson made many series of measurements and obtained the value 299,853 km/sec ± 60 km/sec. In the latter half of the nineteenth century, many measurements using the velocity of electromagnetic radiation or the ratio of electromagnetic to electrostatic units were conducted. The results are very similar to the previous ones. Currently, the recommended measured value of the speed of light on the earth, *c*, is equal to 299,792.5 km/sec.

In 1905, Einstein published his special theory of relativity based on the following two postulates: 1. The laws of physics are the same in all inertial frames. 2. The speed of light in vacuum is constant regardless of any reference frame.

Dickey et al. reported observation of the time taken by the laser light to go to the Moon and back to the earth over the last forty years and the result implied a decrease of the speed of light. Anderson et al. analyzed radio tracking data from Pioneer 10/11 spacecrafts and suggested that the speed of light might is less than the common known value of c.

In 1908, Ritz assumed that the speed of light might be influenced by the motion of the source,

$$c' = c + u\,, \tag{1}$$

where c is the speed of light from a resting source, i.e. the well-known value, u is the relative velocity of the source and the detector, c' is the apparent speed of light from the moving source. In this paper,

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we use the star as the light source and place the detector on the earth, so the light source and the detector have relative motion.

Table 1 shows the radial velocities, magnitudes, spectrum bands, right ascensions, declinations, and distances of Capella, Betelgeuse, Arcturus, Adlebaran, and Vega from the sun. The data in Table 1 come from different references. They may have small variation.

Figure 1 is a sketch of a celestial sphere and positions of the stars. The orbital speed of the earth, V_e, is about 30 km/sec which is on the ecliptic plane. Let V_s denote the radial velocity of the star from the sun and $\overline{AB}$ be the projection of the radial line of the star on the ecliptic plane. θ is the angle between V_e and $\overline{AB}$, φ is the angle between V_s and $\overline{AB}$. So the projected orbital velocity of the earth on V_s is $V_e \cos\theta \cos\varphi$. The relative radial velocity of the star and the earth V_r is $V_s - V_e \cos\theta \cos\varphi$.

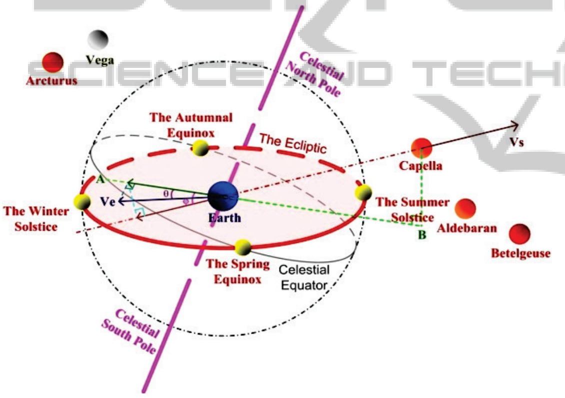

Figure 1: The sketch of celestial sphere, positions of Capella, Betelgeuse, Arcturus, Aldebaran, Vega (not on scale), the radial velocities of Capella and the earth, and θ and ϕ.

2 SYSTEM DESIGN PRINCIPLE

Some of physical parameters are dimensionless, others are dimensional and their numerical values depend entirely on the units in which they are defined. The speed of light is dimensional and expressed in terms of length per unit time. To measure the speed of light, we need a rule and a watch. Expecially to measure the speed of light emitting from a moving source, we encounter the simultaneity problem. Conventionally the detector and the moving source are considered in two different reference frames. In 1892, H. A. Lorentz proposed the Lorentz Transformation as follows:

If the relative motion of the two reference frames is along their *x* and *x'* axes, the first frame with the space and time units x' and t' moves to the right with speed relative to the second frame with space and time units *x* and *t*, then

$$x' = \frac{(x - vt)}{\sqrt{1 - {v^2}/{c^2}}} \tag{2}$$

$$t' = \frac{(t - {vx}/{c^2})}{\sqrt{1 - {v^2}/{c^2}}} \tag{3}$$

$$y' = y \tag{4}$$

$$z' = z \tag{5}$$

$$x = \frac{(x' + vt')}{\sqrt{1 - {v^2}/{c^2}}} \tag{6}$$

$$t = \frac{(t' + {vx'}/{c^2})}{\sqrt{1 - {v^2}/{c^2}}} \tag{7}$$

$$y = y' \tag{8}$$

$$z = z' \tag{9}$$

where *v* is the relative speed.

In our design, we will avoid using the units transformation and simultaneity problem. We compare the appearent speed of starlight with the well-known value, *c*. Therefore, we only use the space and time units on the earth, in other words, we have one rule and one clock. Also because the speed of light is about 3×10^8 m/sec which is extremely fast, the speed of an ordinary moving light source on the earth is much less the speed of light. To investigate the influence of the speed of a moving light source on the light speed measurement is a difficult task. However the universe provides the experimental environment.

Our measurement system consists of a transmitter and a distant receiver. At the transmitter, we used a telescope to collect the light from Capella, Betelgeuse, Arcturus, Adlebaran, and Vega. These stars are bright and have large relative radial velocity with respect to the earth around the Spring Equinox. Then we modulated the starlight, terrestrial 635 nm red light, and 1550 nm infrared light into pulses simultaneously. After travelling a distance, d, these pulses arrived at the receiver. The red light travelled along almost the same path of the starlight. So we were able to use the red light and the 1550 nm infrared pulses as the reference and trigger signals.

We used the terrestrial white light which travelled along exactly the same path of the starlight.

If the speed of light is constant, the travelling time of starlight pulses and the terrestrial white light pulses from the transmitter to the receiver should be the same as

$$t_1 = d/c \tag{10}$$

If Ritz's assumption is valid and the speed of starlight has deviated from the well-known value, c, then the time taken for the starlight pulses travelling from the transmitter to the receiver is given by

$$t_2 = d/(c - V_r) \tag{11}$$

where V_r is the relative velocity of the star and the earth.

3 SYSTEM DESCRIPTION

Based on the design principle and concept described in the previous section, we have two different designs: one using a rotating two-facet mirror and a slit to modulate the continuous light beam into pulses and the other employing a chopper.

3.1 The Optical System using a Rotating Two-facet Mirror and a Slit

Figure 2 shows the schematics of the system layout. At the transmitter, for the starlight path, we used the one-meter telescope of the Lulin Observatory to collect the starlight. One end of a five-meter fiber with core diameter of 68 μm and the numerical aperture about 0.0729 was placed at the focal point of the telescope to guide the starlight. The other end of the fiber was fixed at the focal point of the off-axis parabolic mirror, P1, which made the ray collimating. It was then reflected by the rotating mirror, M1, and was incident upon the off-axis parabolic mirror, P2. A 100 μm wide slit was located at the focal point of P2 and another off-axis parabolic mirror, P3. When the rotating mirror M1 spun, the light would scan across the slit to produce light pulses. The pulses were reflected by P3 to the planar mirrors, M2 and M3, where M3 was located at the Tungpu Hostel about 2,147 m from the Lulin Observatory. The collimating ray from M3 travelled 2,155 m back to the Lulin Observatory to reach the 30 cm off-axis parabolic mirror, P4. A photo-multiplier tube (PMT) was placed at the focal point of P4. Therefore, the total travel distance, d, was 4,302 m.

For the path of the reference red light, a laser with a wavelength of 635 nm and a 4 μm single mode fiber pigtail was used as the reference light source. The end of the fiber was located at the focal point of the lens, L1. The collimating ray from L1 was incident to the rotating mirror, M1, and then the lens, L2, with a standard 62.5 μm multimode fiber

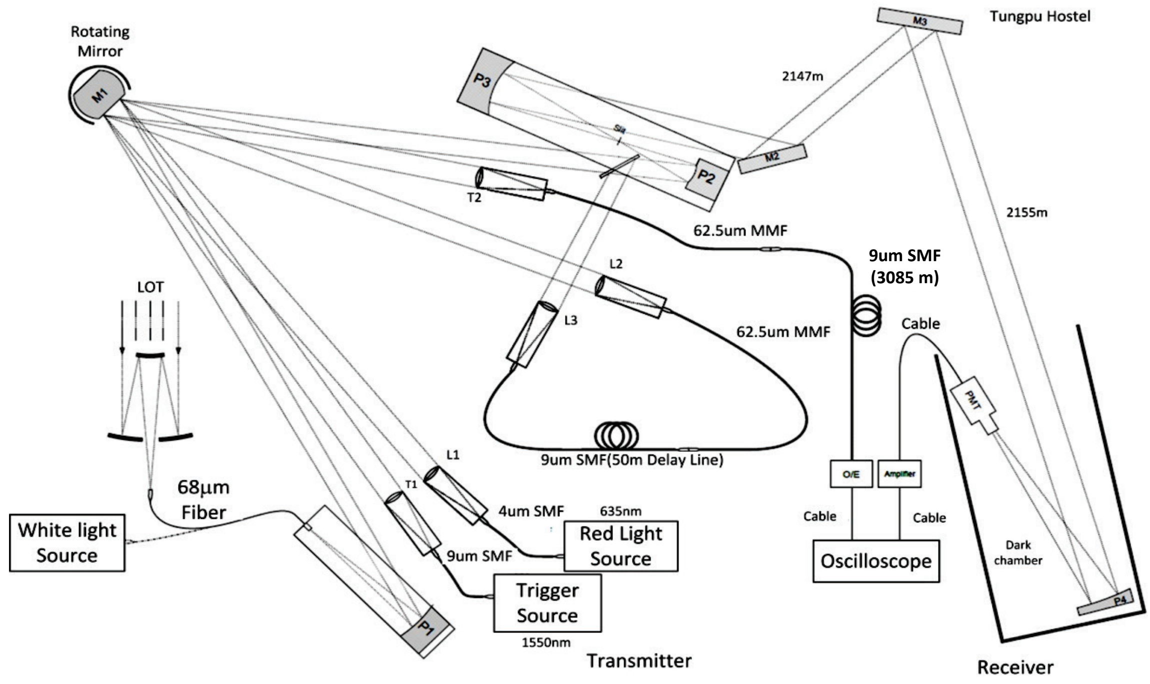

Figure 2: The schematics of the optical system using rotating mirror.

connected a 9 µm single mode fiber located at the focal point. The 62.5 µm fiber acted as a slit and guided the pulses. The total length of this fiber link was 63 meters, which separated the red light and starlight pulses by about 300 nsec on the oscilloscope screen when M1 spun at 17,929 rpm. The other end of the single mode fiber of the link was placed at the focal point of the lens, L3. Then the collimating ray from L3 was combined with the starlight by a beam combiner BS1. Thereafter the red light and the starlight pulses travelling along the same path were received by the PMT to convert them into electrical pulses which could then be recorded by the oscilloscope. For the trigger signal, a 1550 nm laser with an Erbium doped fiber amplifier and a 9 µm single mode fiber pigtail was used as the trigger source. The end of the pigtail fiber was placed at the focal point of the lens, T1. The collimating ray from T1 was incident to M1 and then the lens, T2. At the focal point of T2, we had a standard 62.5 µm multimode fiber which acted as a slit and guided the pulses through the 3085-meter single mode fiber to the receiver. A photodetector was employed to convert the infrared pulses to electrical pulses which were used as the trigger signal for the oscilloscope.

3.2 The Optical System Employing a Chopper

When we use the rotating two-facet mirror and a slit as a modulator, the reflected beam from the mirror M1 scans over the slit to product the pulses while the rotating mirror spun. The spindle which drives the rotating mirror may have wobble and the angular velocity deviation. Here we propose the optical system using a chopper as the modulator. In this system the light beam is fixed. When the chopper spins the light beam is modulated into pulses. Figure 3 is the schematics of the optical system using a chopper. The starlight is collected by the telescope and guided by the 68 µm fiber whose output end is placed at the focal point of P1. The reflected collimating beam is incident to M1, M12 and P2. The focal point of P2 and P3 is at the slit of the chopper. The reflected collimating beam from P3 then is incident to the planner mirror M2 and transmits over 4.3 km to P4. The PMT is located at the focal point of P4. The 1550 infrared is collimated by the lens L1 and then combined by the beam splitter, BS1, with the starlight main path.

After the chopper, part of the 1550 nm light is separated by the P90 beam splitter and through the lens L2 and incident to the multimode fiber connected to the 3.8 km single mode fiber delay line.

At the end of the single mode delay line, the 1550 nm optical/electrical converter converts the

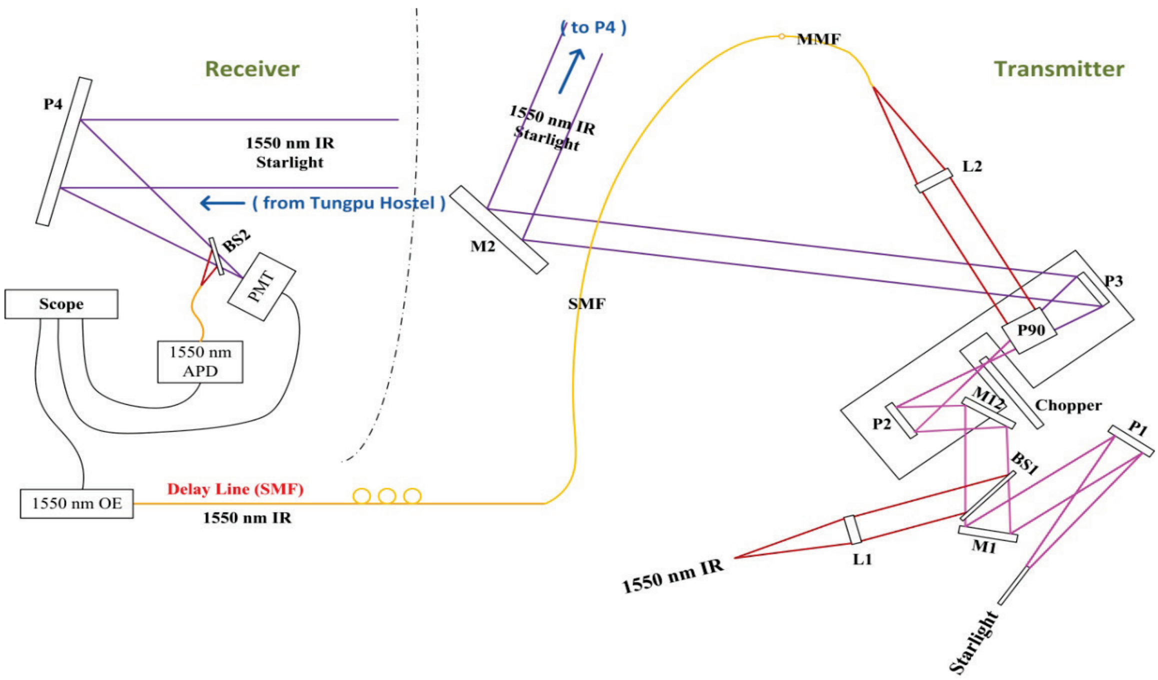

Figure 3: The schematics of the optical system using chopper.

optical signal to the electrical signal. The rest part of 1550 nm travels along with the starlight and reaches the receiver where the beam splitter BS2 and an Avalanche Photon-Diode are used to separate the 1550 nm light and converts to the electrical signal.

When the chopper spins, the starlight and the 1550 nm infrared are modulated into pulses simultaneously. The two 1550 nm pulses at the receiver can be used as the trigger and the reference signals. In this system, the chopper is a very important element, which must be light weight and easy to have dynamically balanced. We have used titanium alloy and composite carbon fiber to fabricate the chopper. However the preparation is still on-going.

4 MEASUREMENT RESULTS

We used the optical system using the rotating mirror and the slit to perform the measurement in November 2009, March 2010, and January 2011. In order to minimize the error due to deviation of the spindle speed, we carefully aligned the parabolic mirrors and the lenses P1, P2, T1, T2, L1 and L2, such that the three beams from P1, T1, and L1, after reflected from the rotating mirror M1, were simultaneously incident to the slit after P2, the focal points of T2 and L2, respectively.

Because the optical power of the starlight was very low (in the order of a few nanowatts or less), the PMT operated in the photon counting mode which generated spikes instead of full waveforms. The maximum amplitudes of dark current and thermal noises were 0.024 volts and very small compared to the spikes and trigger pulses. To avoid accumulation of noises, we first choose a threshold at 0.025 volts and set all recorded data smaller than the threshold to zero. If there are spikes in the frame, we classify it as a valid frame, otherwise we discard it. To reconstruct the starlight and the red light pulse waveforms, taking a moving average of length 100 on the trigger pulse of each valid frame, we calculate the centroid (center of gravity) by the weighted time average method, i.e. $X_{centroid} = \sum X_i Y_i \big/ \sum Y_i$, where X_i is the sampling time and Y_i is the amplitude which is larger than 20% of the peak value. Then we adjust the time axes of the frames by aligning the centroids of the trigger pulses for 2,000 valid frames and simultaneously accumulate spikes to form the waveforms of the starlight and the red light pulses. Because the PMT operated in the photon counting mode, we only take the peak value of the spike during the accumulation process. We apply Gaussian fitting to the red light waveform to obtain the centroid. After finishing this process for the entire set of starlight measurement frames, we align the centroids of the fitted red light pulses to reconstruct the complete waveforms of the starlight and the red light pulses. We follow the same procedure to reconstruct the pulse waveforms of the terrestrial white light and the red light.

Next, we again use Gaussian fitting to estimate the centroids of the starlight, white light, and red light pulses. We applied different fitting methods and obtained a similar result.

In the spring of 2013, we used the similar setup as shown in Figure 2 to measure the speed of starlight, where we omitted the red light and used the 1550 nm as the trigger and the reference signals. We obtained the similar result as the previous ones. Table 2 summarizes the average delays of the starlight measured in 2010, 2011, 2012, and 2013. Note that if the starlight pulses arrive at the receiver earlier than the terrestrial white light pulses, the delay value is negative, e.g. the Vega pulses.

The pulses of Adlebaran, Capella, and Betelgeuse have positive delays and that of Vega and Arcturus have negative delays. As shown in Table 1, the relative radial velocities of Adlebaran, Capella, and Betelgeuse are positive, but that of Vega and Arcturus are negative. Because we had laid the equipment on the floor of the Lulin Observatory, the ambient temperature and the relative humidity made the floor contraction or expansion which affected the measurement. The error of delays of Arcturus in 2011, Vega in 2011, and Capella in 2012 are large.

5 CONCLUSIONS

In this paper, we presented a novel method to measure the speeds of starlight. This method compares the travelling times of these starlights and the local white light from the transmitter to the receiver. Such that physical unit transformation, clock synchronization and definitions of dimension units problems can be avoid. This system utilizes the existing telescope of the observatory, the orbiting speed of the earth, and the radial velocities of stars. Comparing the measured apparent speeds of Adlebaran, Capella, Betelgeuse, Arcturus, and Vega with the well-known speed of light from a rest source, c, we find that Adlebaran, Capella, and Betelgeuse have positive delay, while Vega and Arcturus have negative delay. Note that Adlebaran,

Table 1: The data of Capella, Betelgeuse, Arcturus, Adlebaran, and Vega.

Star	Capella	Betelgeuse	Arcturus	Vega	Adlebaran
Apparent Magnitude	0.91/0.76 (B-V)	0.58 (V)	-0.04 (V)	0.03 (V)	0.85 (V)
Stellar Classification	G8 III / GI III	M2 Iab	K2 III	A0 V	K5 III
Right Ascension	5h16m41s	5h55m10s	14h15m39s	18h36m56s	4h35m55s
Declination	+45°59'52"	+7°24'25"	+19°10'56"	+38°47'01"	+16°30'33"
Radial Velocity V_s	29.65	21.91	-5.19	-13.9	54.26
Distance (light year / parse)	42.5 ± 0.5 / 13.04 ± 0.03	643 ± 146 / 197 ± 45	36.7 ± 0.3 / 11.24 ± 0.09	25.3 ± 0.1 / 7.76 ± 0.03	65 ± 0.1 / 20.0 ± 0.4
Relative Radial Velocity (km/sec) (March 18, 2010)	56.47	49.56	-20.77	-27.10	82.43

Table 2: The average delays of starlight measured in 2010, 2011, 2012 and 2013.

	Delays (ns)			
	2010	**2011**	**2012**	**2013**
Adlebaran				2.40
Capella	2.28	2.41	4.57	1.20
Betelgeuse	1.19	1.80		
Arcturus	-0.45	-4.01		-0.19
Vega	-1.35	-7.40		-1.20

Capella, and Betelgeuse have positive relative radial velocity, Vega and Arcturus have negative relative radial velocity, i.e. Adlebaran, Capella, and Betelgeuse are leaving away from the earth and Vega and Arcturus are approaching to the earth. The result implies the measured apparent speed of starlight likely relates to the relative motion of the source and the detector.

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