Test of Multi-object Exoplanet Search Spectral Interferometer

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ABSTRACT

Exoplanet detection, a highlight in the current astronomy, will be part of puzzle in astronomical and astrophysical future, which contains dark energy, dark matter, early universe, black hole, galactic evolution and so on. At present, most of the detected Exoplanets are confirmed through methods of radial velocity and transit. Guo shoujing Telescope well known as LAMOST is an advanced multi-object spectral survey telescope equipped with 4000 fibers and 16 low resolution fiber spectrographs. To explore its potential in different astronomical activities, a new radial velocity method named Externally Dispersed Interferometry (EDI) is applied to serve Exoplanet detection through combining a fixed-delay interferometer with the existing spectrograph in medium spectral resolution mode (R=5,000-10,000). This new technology has an impressive feature to enhance radial velocity measuring accuracy of the existing spectrograph through installing a fixed-delay interferometer in front of spectrograph. This way produces an interference spectrum with higher sensitivity to Doppler Effect by interference phase and fixed delay. This relative system named Multi-object Exoplanet Search Spectral Interferometer (MESSI) is composed of a few parts, including a pair of multi-fiber coupling sockets, a remote control iodine subsystem, a multi-object fixed delay interferometer and the existing spectrograph. It covers from 500 to 550 nm and simultaneously observes up to 21 stars. Even if it's an experimental instrument at present, it's still well demonstrated in paper that how MESSI does explore an effective way to build its own system under the existing condition of LAMOST and get its expected performance for multi-object Exoplanet detection, especially instrument stability and its special data reduction. As a result of test at lab, inside temperature of its instrumental chamber is stable in a range of ±0.5degree Celsius within 12 hours, and the direct instrumental stability without further observation correction is equivalent to be ±50m/s every 20mins.

Keywords: Exoplanet detection, Radial velocity measurement, Multi-object observation, Fixed delay Interferometer, Interference spectrum

1. INTRODUCTION

Guo shoujing Telescope well known as LAMOST is an advanced multi-object spectral survey telescope equipped with 4000 fibers and 16 low resolution fiber spectrographs. It smoothly serves large area spectral survey with low resolution of R=1,000 – 2,000 every observation night. And the number of effective spectral data had already been more than 2 million in total by the end of 2013. At the meantime, scientists and instrumentation developers never stop their steps to

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explore its potential in different astronomical fields. On one hand, a single-object high resolution spectrograph is under the development as one of its next generation instrumentations now. On the other hand, multi-object Expolanet detection has always been paid our attention very much since spectral survey was successfully carried out. The reason why put focus on this science field is definitely that Exoplanet research will be part of puzzle in astronomical and astrophysical future, which contains dark energy, dark matter, early universe, black hole, galactic evolution and so on. When Kepler releases too big number of observation information to be processed in a few years, we're quite surprised and get more confidence to explore LAMOST's potential in multi-object Exoplanet detection.

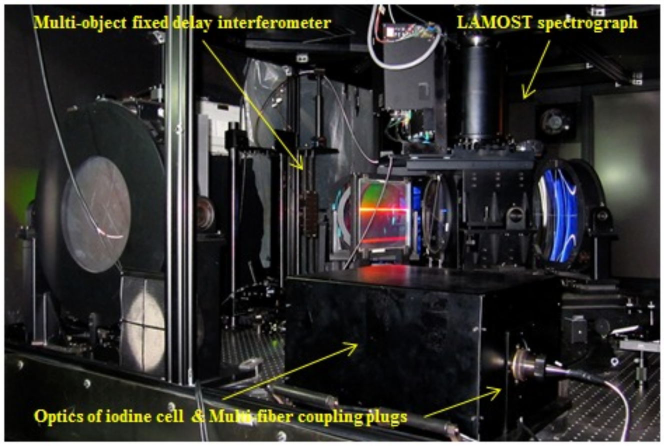

Figure 1. Photo of MESSI at enclosure chamber

$$\Delta V = \frac{C\lambda}{2\pi d}\Delta\varphi \tag{1}$$

Table 1. MESSI specifications

Parameter	Value
Max. number of simultaneous observation	21
Band	500 – 550 nm
Telescope Aperture	Φ4,000 mm
Fiber core diameter	Φ320um (3.3")
Resolution of spectrograph	R=5,000 – 10,000

Developing a multi-object Exoplanet detection instrument was basically an initial idea inspired by Externally Dispersed Interferometry (EDI) [1] before 2010. This new technology impressed us due to its special feature, which measures radial velocity through interference phase instead of wavelength shift. Interferometer loads additional interference information on stellar spectrum so that stellar Doppler Effect theoretically causes more sensitive phase variation than wavelength shift in the traditional radial velocity method. The equation (1) demonstrates the relationship of radial velocity (ΔV) and interference phase (Δφ), and fixed delay (d) improves measuring accuracy in degree. Moreover, the related instrumentation is technically integrated system with fixed delay interferometer and medium resolution spectrograph as figure (1). Theoretically, spectrograph here gives its dispersion to improve interference contrast and increase sampling number at different wave channels. This possibly help us to develop the expected system based on the present LAMOST spectrograph in medium resolution mode (R=5,000 – 10,000). So far, an experimental instrument named Multi-object Exoplanet Search Spectral Interferometer (MESSI) has already been built and tested at lab. It's able to simultaneously observe 21 objects in a short band from 500 to 550nm, see in table (1). Compared with the other current similar instrumentations, MESSI doesn't only try to get good performance in radial velocity measurement but also research on feasible way to get balance between the current spectral survey and Exoplanet detection. To give clear illustration, session 2# gives instrumentation description, session 3# shows detailed test result and analysis done at lab.

2. INSTRUMENTATION

2.1 Scheme

At the beginning of MESSI development, science motivation strongly required the expected instrument to share telescope and spectrograph with the current observation in peace. An overall scheme was proposed soon that divides the existing spectrograph into two parallel observation modes, respectively spectral survey and multi-object Exoplanet detection as the figure (2). In this scheme, MESSI components besides of spectrograph are defined as a removable system before spectrograph slit, and the existing direct fiber link between telescope and spectrograph is physically cut off so that telescope, spectrograph and MESSI respectively have their own connection ports. This overall scheme gives a way to mount a multi-object fixed delay interferometer in front of spectrograph slit.

But this terminal-switching scheme highlights the importance that telescope efficiently feeds different terminal instruments with standard fiber ports in a simple way. A kind of multi-fiber coupling plugs, which is composed of a receptor, an inserter and a socket, is regarded as the most feasible way to work it out. Every fiber bundle with multi-fiber coupling plugs is able to accommodate 25 pairs of fiber to couple together with high stability and efficiency. And this way also solves well the problem caused by difference of fiber number in both of observation modes. Telescope provides 10 fiber bundles to every spectrograph in spectral survey, and MESSI freely chooses one from these 10 fiber bundles in according to the location of desired objects at telescope focal plane.

It's well known that wavelength calibration is so important as to give direct influence in radial velocity measurement, especially multi-object calibration. Stable spectral profile of chemical elements provides convenient way to calibrate wavelength and gauge its shift in normal radial velocity method. Iodine absorption spectrum has so plenty of spectral information in visible as to be MESSI calibration source. To keep high consistency of iodine spectral profile, how simultaneously dye all of stellar beam by a single iodine cell is another problem can't be avoided in this project. MESSI gives its answer to this question through the using of multi-fiber coupling plugs and dual telecentric optics. The iodine cell locates at the central collimated optics so that minimizes wavefront difference when collimated beam in different field of view goes into iodine cell.

So MESSI components besides of spectrograph clearly contain a multi-object fixed delay interferometer, multi-fiber coupling plugs, optics of iodine cell and artificial light resource, as figure (1) [2]. It seems reasonable that all of components before slit are integrated together as a removable system. But Schmidt optics of spectrograph gives very serious space requirement due to central obscuration in collimator and camera. For simplification, interferometer, iodine cell and artificial light source become three independent components, which connect each other with standard multi-fiber coupling plugs. Only the minimized interferometer is mounted at spectrograph slit, and the other components freely locate on the spectrograph's optical bench.

This serious issue doesn't only happen in hardware development but also troubles data reduction. It leads to variation of spot profile at detector with difference of dispersion and field of view. The complex spot profile of spectrum can't be processed well by normal method in Gaussian profile. Moreover, data reduction is quite different from the existing one applied in radial velocity measurement because of interference spectrum. Although EDI theory gives a definite direction about algorithm of radial velocity, it's still worthy of paying half attention on pre-reduction of raw spectrum in order to really get useful information. So data reduction scheme is supposed to be three parts, respectively data management, pre-reduction and radial velocity solution.

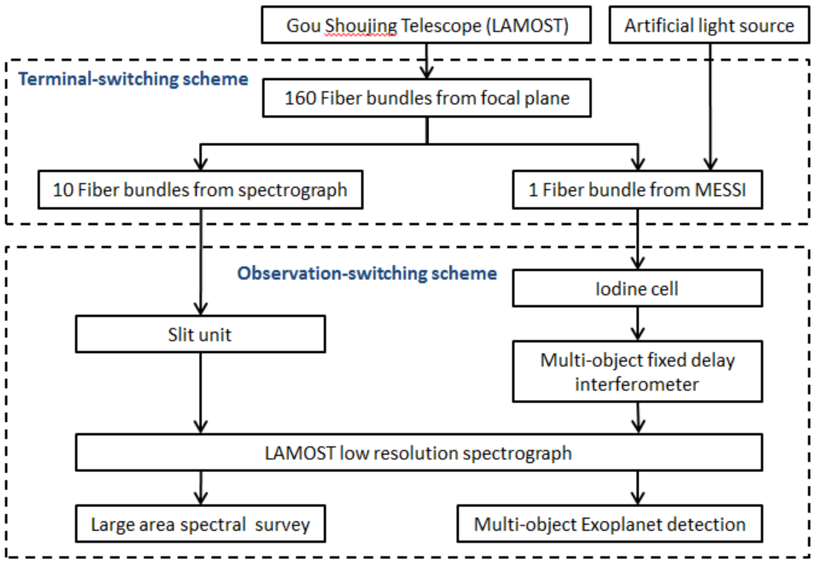

Figure 2. MESSI overall scheme

2.2 Configuration

- Multi-object fixed delay interferometer [3]

Multi-object fixed delay interferometer is in charge of loading external inference information on stellar spectrum. And this desired interferometer is different from conventional Michelson interferometer due to fixed delay. Both of its interference arms (refractive index: n_1, n_2, length: l_1, l_2) don't only provide fixed delay (d) together but also conjugate each other in geometry optics ($n_1\ l_1 = n_2\ l_2$), see in equation (2). Besides of fixed delay, a little linear variation of optical path difference (OPD) is required in spatial direction for interference phase measurement. Since it's hard to get interference fringes at focus, a cylindrical lens in optics diffuses spot at focal plane only in spatial direction so that clearly obtains periodical interference fringes, as figure (3). So it's reason why interferometer development dominates the whole project.

$$d = 2(n_1 l_1 - n_2 l_2) = \frac{2l_1}{n_1}\left(n_1^{\ 2} - n_2^{\ 2}\right) \tag{2}$$

Due to Schmidt optics of spectrograph, all of 21 interferometer units have to be divided to 7 modules, which accommodate 3 units at each module, in order to arrange them in fan-shaped distribution at slit, as figure (3). This figure also shows a kind of folded optical structure used to reduce its cross area up to 45% actually. And an interference component is well fabricated by integrating three conventional prisms, as figure (3). This is key part that provides all of external interference information. When illuminates it with low-voltage Hg lamp, interference fringes easily get good contrast of higher than 0.35 @ 546.1nm.

- Multi-fiber coupling plugs [4]

In telescope terminal-switching scheme, standard multi-fiber coupling plugs are important joints among different instrumentations. It contains an inserter, a receptor and a socket, as figure (4) left. A kind of multi-fiber push on/pull-off (MPO) design is adopted to make sure high coupling efficiency and convenient accessibility. Every fiber independently gets a spring-loaded ceramic ferrule at the ends, and a high drilling-precision coupling cavity. The spring-loaded way is useful to provide steady coupling efficiency in the long term. And independent coupling cavity isolates every fiber pair without interference. To keep coupling action convenient and smooth, a pair of plugs provides 3-step alignment to improve aligning accuracy from 100um to 5um. Due to the limitation of cost, some higher precision manufacturing methods can't be used fully. As a result of efficiency test, average coupling efficiency is about 83%, as figure (4) left.

- Optics of iodine cell

For multi-object observation with identical wavelength calibration, MESSI gives complex dual telecentric optics to answer this question, as figure (4) right. It's able to simultaneously dye all of stellar beams from 25 different objects. At both of ends, socket is regarded as connection port to mount multi-fiber inserter. On the central collimated optics, a transfer mechanism serves to iodine cell for moving in/out of optics. And an additional air cell is at side in order to compensate the optical difference when removes iodine cell. As a result of test, average coupling efficiency is about 81%, but total throughput is only 60% since serious vignette causes during actual manufacture.

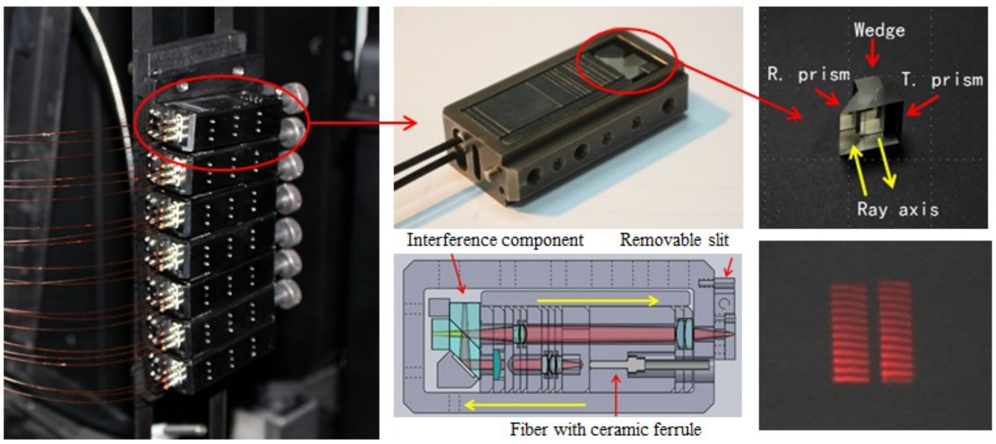

Figure 3. Multi-object fixed delay interferometer

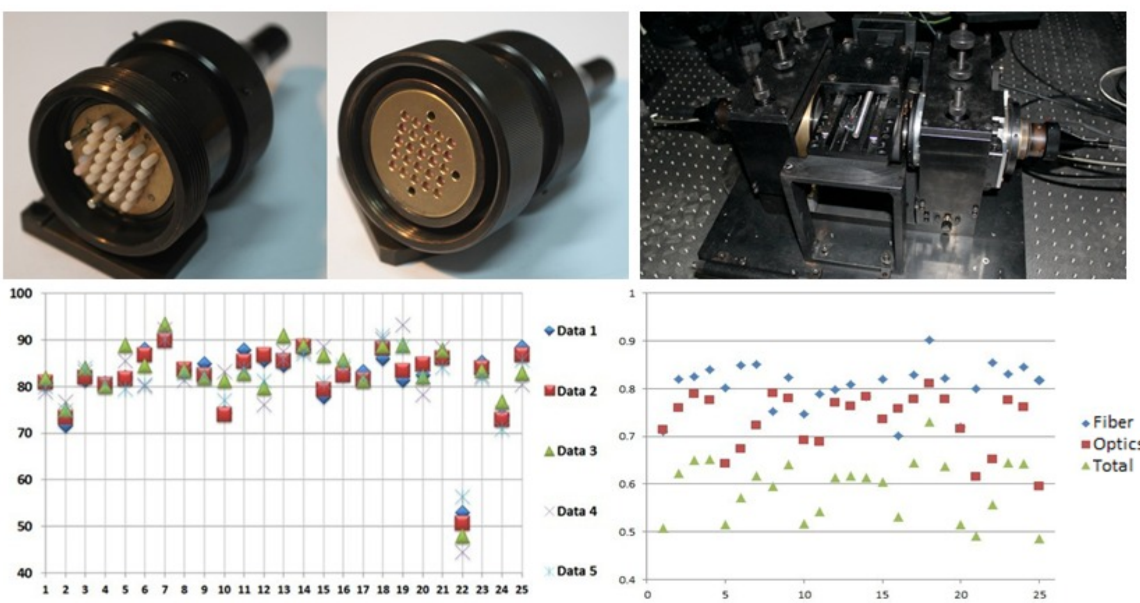

Figure 4. Left: Multi-fiber coupling plugs, Right: Optics of iodine cell

- Data reduction

MESSI data reduction is developed in according to comprehension of EDI theory and characteristics of interference spectrum, and is paid the same attention on pre-reduction to raw data and radial velocity solution. Three main programs, including data management, pre-reduction and radial velocity solution, get convenient and smooth control through a graphic interactive interface, as figure (5) left. In pre-reduction, a fake flat spectrum is generated by a kind of blurring technique, which takes well advantage of interference periodicity, as figure (5) right. Theoretically, every two point separated by π in an ideal sinusoidal period neutralize their phases each other. Moreover, this blurring technique makes contribution on wavelength calibration as well.

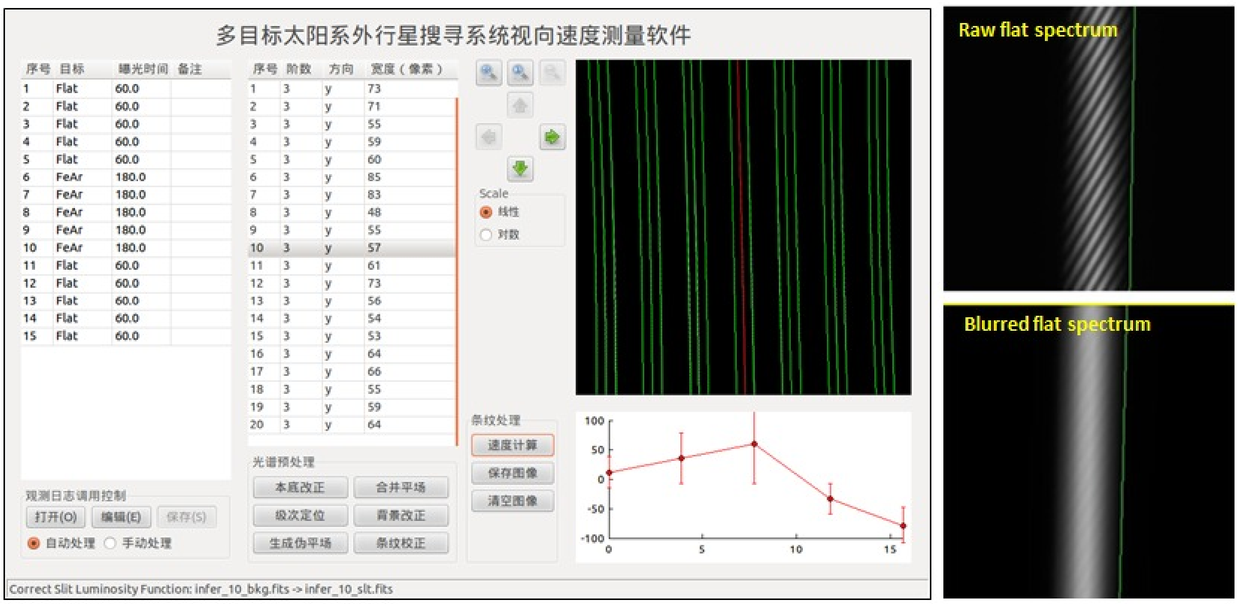

Figure 5. Left: Graphic interactive interface of data reduction, Right: Blurring effect in flat correction

3. PERFORMANCE

3.1 Temperature

The original spectrograph didn't get well-control environment at site, especially temperature, since its science observation is not in strong need of temperature control. But it's well known that radial velocity measurement is quite sensitive to tiny structure variation caused by temperature and vibration. Actually, measuring error increases in random when environmental temperature fluctuates rapidly during exposure time. An enclosure chamber made by industrial polyurethane board provides desired temperature control and scattering elimination in degree, however, detector components in the chamber, especially Dewar and electronic controller, still generate strong internal temperature conversion around them. So MESSI adds a ventilator inside to reduce this temperature fluctuation. As a result of test, the chamber smoothly provides temperature stability of ±0.5 degree Celsius but not completely isolate from outside temperature, as figure (6). And it gets good performance in scattering elimination that background flux reduces by 95%.

3.2 Instrumentation

- Interference spectrum

MESSI successfully gets good quality interference spectrum through spectrograph's detector, as figure (7). Obviously, it's special spectrum with interference information in both of spatial and dispersed direction. Interference phase appears periodical variation with wavelength in dispersed direction. And sinusoidal interference fringes in spatial direction are artificially produced by linear variation of OPD at interferometer, as figure (7).

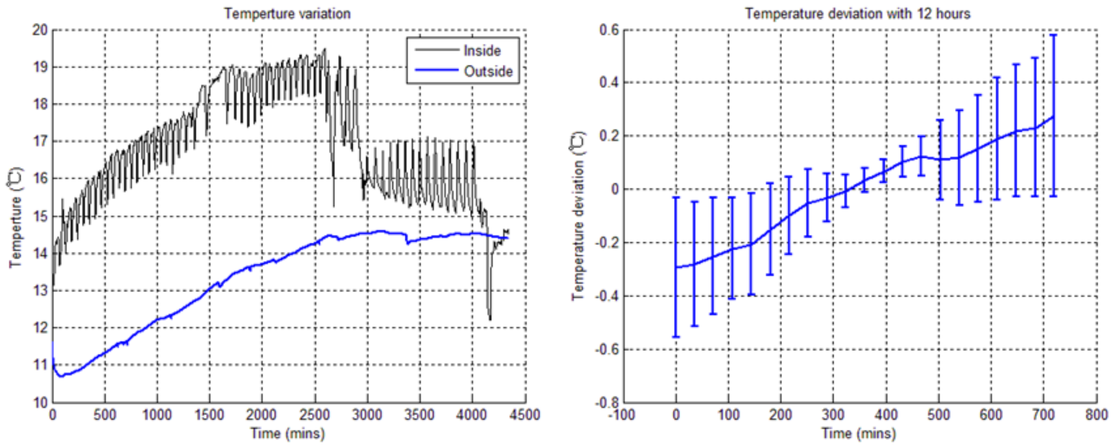

Figure 6. Temperature test (Left: Raw data within 3 days, Right: Temperature deviation within 12 hrs)

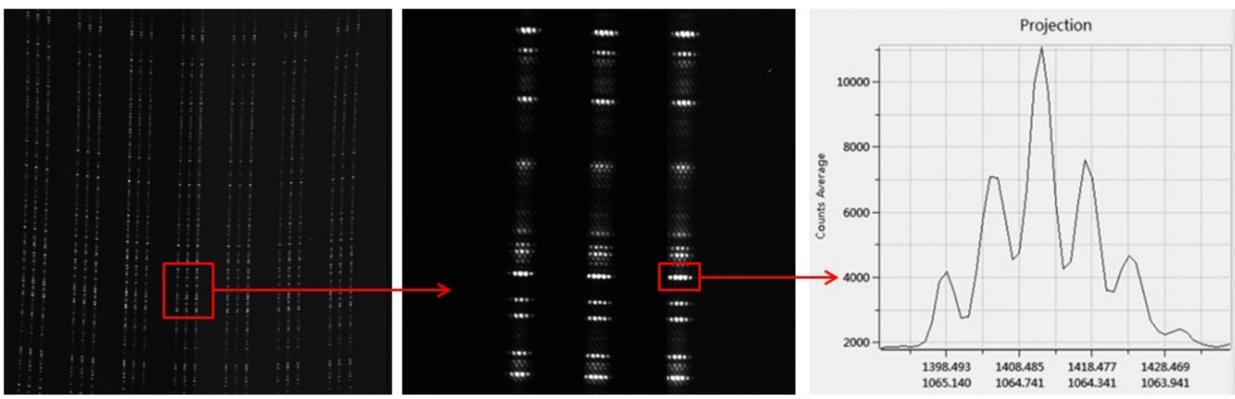

Figure 7. MESSI interference spectrum of ThAr (Left: 21 spectrums, Center: Zoom-in, Right: spectral profile in spatial direction)

- Instrumental stability

Radial velocity measuring precision is the most important performance in Exoplanet detection. Normally, it's relative to spectral resolution, instrumental stability and observation correction. At present, MESSI impossibly gets observation time and feasible access to telescope because the current spectral survey fully occupies observation time of LAMOST, and MESSI needs to cut off the existing direct fiber link for switching modes among terminal instrumentation. So all the test given in paper is completely done at lab, and only indicates instrumental stability without observation correction.

At lab, constant source of chemical element lamp (FeAr) provides testing spectrum instead of stellar. For MESSI, evaluation of instrumental stability gives focus on interference phase variation caused by all kinds of influence during exposure time, especially temperature and vibration. Refer to overall throughput from telescope to spectrograph and observed magnitude in spectral survey, MESSI is capable of getting V=10 stellar spectrum with S/N=100 at an exposure of 1200 seconds. It leads that stability test takes 6 spectrums within 20 minutes, and repeat this process every 2 hours. Below figure (10) respectively gives 4 test results in different times, and represents interference phase variation with equivalent deviation of radial velocity. It indicates that instrument is able to keep its own stability within acceptable range of ±50 m/s under random environmental influence. Moreover, phase consistence among 21 sub-systems is concerned as well as stability since this difference should be compensated when compares some data of the same object taken from different sub-interferometers. Actually, MESSI possibly reaches phase consistence of ±0.25λ through relative comparison.

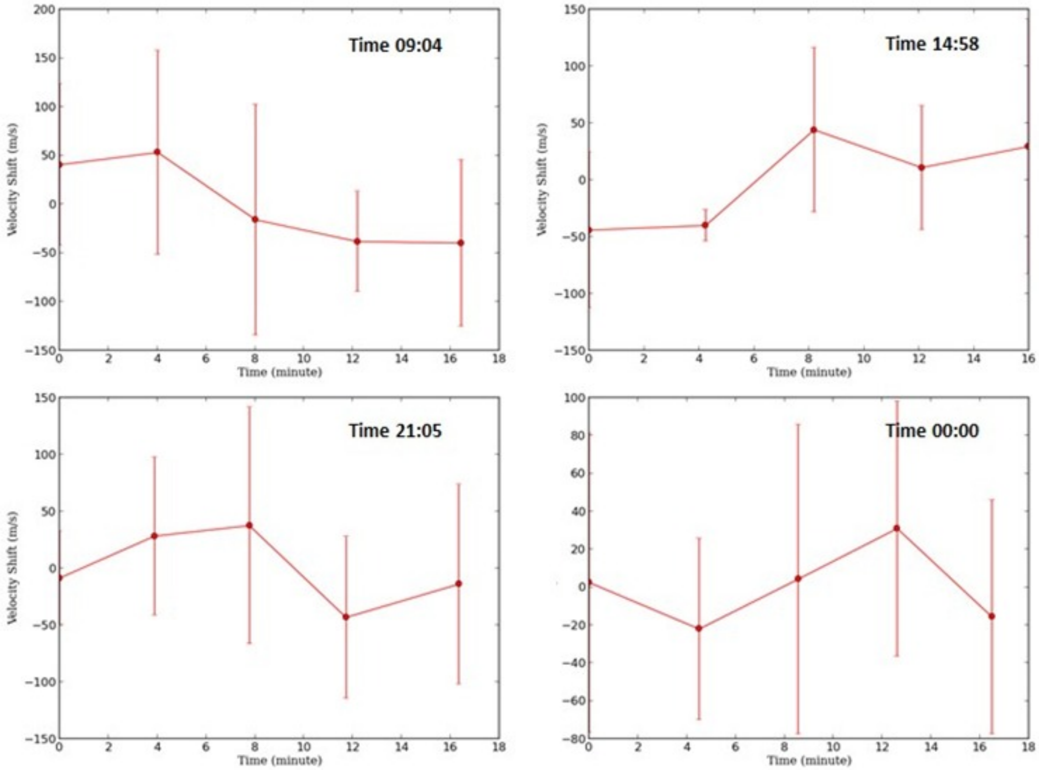

Figure 10. Test result of interference phase stability in different test time

4. ACKNOWLEDGEMENTS

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