Characterization of extra-solar planetary systems requires surveying for planets around hundreds of thousands of nearby stars of all types, with different metallicities, environments (star cluster and multiple star systems), ages etc. Space missions such as SIM, NGST and TPF will identify many of these systems. However, these missions need ground-based surveys to find candidates to improve their efficiency and provide complementary work. Among these surveys, Doppler radial velocity (RV) surveys, which have detected almost all of ~100 known planetary systems, will continue to be the most efficient for detecting planets. Though the cross-dispersed echelle spectroscopy has demonstrated high sensitivity and good efficiency for observing thousands of stars, (limited to late F,G, K and M type), it would be tremendously challenging to search for hundreds of thousands of stars since this would require more than 2 orders of magnitude improvement in observing efficiency. New techniques with high throughput and multi-object capability for high precision RV surveys are crucial in solving this problem. Here we introduce a new technique based on a multi-object fixed-delay interferometer with a first order grating postdisperser which provides the potential for all sky radial velocity surveys for planets.

This kind of instrument is a combination of a fixed-delay interferometer with a moderate resolution post-disperser. Doppler measurements are conducted by monitoring stellar interferometric fringe phase shifts instead of absorption line centroid shifts as in the echelle. High Doppler sensitivity is achieved by optimizing the optical delay in the interferometer and reducing photon noise by measuring multiple fringes over a broadband realized by the post-disperser. Since the resulting Doppler sensitivity is independent of the dispersion power of the post-disperser, the whole instrument can be designed for multiple objects, high throughput, and high Doppler sensitivity, while the instrument can be made very compact, thermally and mechanically rigid, and low-cost compared to the echelles. Its superior stability and simple instrument response allow its easy adaptation to other wavelengths such as UV and IR. Once a multi-object instrument of this type, with possible UV, visible and near-IR instrument channels, is coupled with a wide field telescope (a few degree, such as Sloan and WIYN), it will produce hundreds of fringing spectra to allow simultaneous searching for planets around late type F, G, and K stars in the visible, early type B and A-type stars, and white dwarfs in UV and late M-dwarfs in near-IR.

The first light observations of our prototype interferometer at the Hobby-Eberly 9m and Palomar 5m telescopes in 2001 have demonstrated that this new technique can approach high Doppler precision mainly determined by photon statistics (Ge et al. 2001; van Eyken et al. 2001; Ge et al. 2002). For instance, a stellar intrinsic Doppler precision of ~3 m/s has been achieved with a wavelength coverage of ~140 Å and S/N ~120 per pixel. The overall short-term Doppler measurement error is ~9 m/s. This is mainly caused by low fringe contrast (or visibility) of the iodine absorption lines (~2.5% vs. ~7% in stellar lines) for wavelength calibration. Recent observing at the KPNO 2.1-m telescope demonstrated good instrument throughput and increased wavelength coverage. The total detection efficiency including the sky, telescope and fiber transmission losses, the instrument and iodine transmission losses and detector quantum efficiency is 3.4%

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under 1.5 arcsec seeing conditions. This efficiency is already comparable to all of the echelle spectrometers for planet detection.

**Keywords:** Interferometer, spectrometer, fringe, multi-object, Doppler, Radial Velocity, Extra-solar planets,

1. **Introduction**

Since the discovery of 51 Peg B (Mayor & Queloz 1995), the number of known planets has gone up dramatically and today about 100 such companions are known with 7 of these systems showing multiple planets. Most of these systems have been discovered using high resolution echelle spectrographs. These instruments are routinely achieving a radial velocity precision of $\sigma = 5$-15 m/s and even as low as 3 m/s in the best cases (Butler et al. 1996; Vogt et al. 2000). The echelle spectrographs themselves are large and expensive, with a complicated point spread function which has to be modeled appropriately. The high resolution along with the large wavelength coverage is paid for by the huge costs, the complexity of the instrument and the low throughput of around 1-4% (Vogt et al. 2000; D’Odorico et al. 2002). The observational challenge now lies in detecting as many of these systems as possible to understand the statistical distribution of planetary masses and distances from the host star. Detecting a large sample of planets will also help in understanding the physical processes underlying planetary formation. A larger sample of stars needs to be surveyed with velocity precision less than 10 m/s to make this possible. In addition, the Space Interferometric Mission (SIM) will also need to survey thousands of faint stars ($V = 11$-$13$ mag) for its grid star network. Such a task will need large amounts of time on telescopes with current echelle technology and this is a significant challenge. The next generation of radial velocity survey instruments must have higher efficiencies, should be able to do multi-object radial velocity surveys and must extend the wavelength range of these searches. The development of our instrument, a multiple object fixed-delay interferometer, a new generation radial velocity (RV) instrument, has been driven in part by these needs.

2. **Principle and Unique Properties of Fixed-delay Interferometer**

The use of a fixed-delay interferometer for Doppler measurements is completely different from the current echelle approach. Instead of measuring the absorption line centroid shifts in the echelle approach, the RV is measured through monitoring interference fringe shifts (Figure 1). The original idea for using a fixed-delay interferometer for high precision Doppler RV measurements was proposed by a Russian solar astrophysicist in the 1980’s (Kozhevatov 1983). This interferometer with a narrow band pass has been successfully used for very high Doppler precision measurements of the Sun (~ 3 m/s, Kozhevatov et al. 1995, 1996; sub m/s precision for the GONG measurements, Harvey 2002 private communication). The concept of combining of a fixed-delay interferometer with a

![Figure 1. Principle of a fixed-delay interferometer.](image1)

The fringe data was taken with a prototype instrument, called Exoplanet Tracker (ET), developed at Penn State (Ge et al. 2001; Ge et al. 2002b). The stellar interference fringes, formed by a Michelson type interferometer with ~ 7 mm optical delay, lie in the horizontal direction and are sampled by ~ 70 pixels. The fringes over different wavelengths are separated by a first order diffraction grating with a resolving power of $R \sim 6,700$, (a factor of ten times lower than typical echelle spectrographs), and recorded in the vertical direction of a 1k×1k CCD.
moderate resolution spectrometer for broad band operations for high precision stellar Doppler measurements was proposed by Dave Erskine at LLNL in 1997. The initial lab experiments and telescope observing with a prototype demonstrated its feasibility (Erskine & Ge 2000; Ge et al. 2002a). A theory for this new instrument concept was developed by Jian Ge (Ge 2002). In this interferometer approach, the instrument response, determined by the two beam interference, is a simple and well-defined sinusoidal function. For comparison, the echelle response is considerably more complex due to the interference among thousands of divided beams from grating steps.

In a fixed-delay interferometer (FDI), a fixed optical delay, \(d\), is applied to one of the beams. Therefore, the interference happens at very high interference order, \(m\), determined by \(m = \frac{d}{\lambda}\), where \(\lambda\) is the operating wavelength. The Doppler RV motion will shift the fringes of stellar absorption lines to neighboring orders. The corresponding Doppler velocity shift is

\[
\Delta V = \frac{c\lambda}{d} \Delta m = \frac{c\lambda}{d} \frac{\Delta \phi}{2\pi},
\]

where \(\Delta \phi\) is the measured phase shift of a fringe. If the absorption line density is constant over the observed band, then the total observed Doppler error is

\[
\sigma_{\text{obs, interference}} \approx \frac{1}{\sqrt{N_o \cdot D_o \cdot F_o}} \approx \sigma_{\text{obs, interferometer}}
\]

where \(N_o\) is the total number of absorption lines covered by the array, \(D_o\) is the observed absorption line depth, \(l_c = \frac{\lambda^2}{\Delta \lambda_i}\) is the coherence length of the interferometer beam for a bandwidth of \(\Delta \lambda_i\), the intrinsic width of typical stellar absorption lines, \(F_o\) is the observed flux within each observed fringe (or absorption line), and \(\sigma_{\text{obs, interference}}\) is the intrinsic Doppler precision at infinite spectral resolution of a post-disperser (see Ge 2002 for details). This indicates that the Doppler sensitivity of the FDI is independent of the spectral resolving power of the post-disperser, contrary to echelle spectroscopy. In the echelle, the Doppler RV error per spectral line at an infinite spectral resolution, derived from the centroid shift of a line, is

\[
\sigma_e \approx \frac{1}{\sqrt{N_{\text{pix}} \cdot D \cdot \frac{S}{N}}} \frac{1.1c \Delta \lambda_i}{D \lambda \sqrt{F}}
\]

assuming that the intrinsic line profile is Gaussian with a line depth of \(D\) and the flux of \(F\), the FWHM of the line is sampled with \(N_{\text{pix}}\) pixels, and the central 2\(\Delta \lambda_i\) are used for Doppler measurements. If the observed wavelength coverage is not limited to the iodine visible absorption band, then the total observed Doppler error is

\[
\sigma_{\text{obs, echelle}} \approx \frac{1}{\sqrt{N_o \cdot D_o \cdot \lambda \sqrt{F_o}}} \approx \left(\frac{\Delta \lambda_o}{\Delta \lambda_i}\right)^2 \sigma_{\text{obs, interference}} \approx \frac{\Delta \lambda_o}{\Delta \lambda_i} \sigma_{\text{obs, interference}},
\]

where the observed line FWHM is \(\Delta \lambda_o = \sqrt{\Delta \lambda_i^2 + \Delta \lambda_e^2}\), and \(\Delta \lambda_e\) is the FWHM of the echelle response. The Doppler error in the echelle approach strongly depends on the echelle resolving power and stellar intrinsic line width (Bouchy et al. 2001; Ge 2002). Figure 2 shows direct comparison between Doppler errors in the interferometer and echelle for the same photon flux and wavelength coverage. For a solar type star with absorption lines of FWHM \(\sim 5\) km/s (Dravins 1987), at moderate resolution (such as \(\Delta \lambda_o \sim 10 \Delta \lambda_i\), or \(R \sim 6000\)), the echelle approach has \(\sim 10\) times higher Doppler error than the interferometer approach. At high resolution, such as \(R \sim 60,000\), being used for planet detection (e.g., Vogt et al. 1994; D’Odorico et al. 2000), the Doppler sensitivity for a solar type star is still \(\sim 1.4\) times worse than the interferometer.

The independence of Doppler sensitivity from the post-disperser resolving power in the interferometer approach opens up new possibilities for RV studies. The use of low resolution but high efficiency post-dispersers can significantly boost the overall detection efficiency, dramatically reduce the instrument size.
and cost and allow single dispersion order operations for multiple object observations. Full sky coverage for an RV survey for planets becomes possible with wide field telescopes. **Multiple object capability is one of the most significant advantages for this interferometer approach.** The simple and stable response function in the interferometer approach leads to potential low systematic errors, which may allow this approach to reach sub m/s Doppler precision.

Another exciting possibility with this interferometer technique is to extend RV surveys to wavelengths other than the visible, previously not covered by echelle surveys. Since the interferometer response is simple and stable, there is no need to calibrate the instrument response in contrast to the echelle; only wavelength calibration is required. Hence, reference sources with a lower line density than the iodine, which is popularly used in the echelle, can be used. Therefore, this instrument can be easily adapted to other wavelengths, in which more photon flux and stellar absorption lines are available for precision Doppler RV measurements. For instance, late M, L and T dwarfs have peak fluxes in the near-IR. Integration time can be significantly reduced if the IR spectra can be monitored. B and A main sequence stars and white dwarfs have very broad intrinsic absorption lines dominated by the Balmer series. Based on Eq. (2), the intrinsic Doppler error for each Balmer line is about the same as that for late type stars. Since there are only a few dozen broad lines that can be used for early type stars while ~ 1000 lines can be used for late types, the overall observed Doppler error is about ~ 10 times higher for the early types than late types for the same S/N data. Since early type stars are usually much brighter in the near UV than late types at the same astronomical distance (e.g. an A star is about 100 times brighter than a G type star in the visible), it is possible to achieve ~ a few m/s Doppler precision by increasing S/N by a factor of ~ 10.

### 3. Performance of a Prototype Fixed-delay Interferometer

In 2000-2001, we developed the prototype ET, similar to an earlier version built by Jian Ge and his collaborators at LLNL (Ge et al. 2002a). A schematic is shown in Figure 3. It was designed for studying the feasibility of this new approach. The instrument consists of a Michelson type interferometer, a modified 1 meter Czerny-Turner commercial spectrometer with a 100 mm diameter collimator beam and a 1k×1k Photonics CCD camera with 24 µm pixel size. The spectrometer can accept f/10 or slower incoming beams without vignetting.

The first light stellar observations with ET were conducted at the Hobby-Eberly 9 m telescope (HET)
in October and November 2001 (Ge et al. 2001). The spectral resolution of the post-disperser is set to \( R = 6700 \). Each resolution element is sampled by 6 pixels. Part of the raw fringe data recorded on the 1k×1k CCD from Aldebaran (\( V = 0.85 \) mag., K5III) is shown in Figure 1. Weighted mean fringe visibilities for stellar fringes and iodine fringes are 7.0% and 2.5%, respectively. The mean estimated Doppler errors for stellar and iodine fringes are 2.7 m/s, and 6.5 m/s, respectively, on the night of 1 November 2001 as shown in Figure 4. The errors are obtained from a statistical analysis using the curve-fit errors from the data. The estimated Doppler error for the combined stellar and iodine spectra is 7.0 m/s. The measured velocity drift over ~ 1.5 hours is consistent with the predicted RV variation due to the Earth’s rotation. The residual Doppler error after the Earth’s rotation RV components are subtracted is 9.4 m/s, indicating possible additional Doppler errors introduced either by the instrument or by data analysis or possible stellar activity. Our Doppler precision at the HET is approaching the photon-noise limit. This is demonstrated through a direct comparison between predicted RV errors and measured values as shown in Figure 5. The theoretically predicted RV errors are based on Eq. (2). Both errors are consistent with each other. This figure also indicates that the iodine calibration contributes major errors in the measurements due to its very low fringe visibility compared to that for the star.

The ET was further tested at the Palomar 5-m telescope in Dec. 2002. Three important experiments were conducted during three days’ engineering run: testing the instrument stability over a longer time than before; testing suitability of ThAr lamp for calibrating instrument drift; and studying feasibility for multi-object capability with the interferometer.

Figure 4. (a). Measured RV variation of Aldebaran vs. observing time at the HET. (b). Doppler RV measurement errors associated with photon statistics in the data.

Figure 5. Doppler velocity error vs. S/N. The solid lines represent theoretical relations between RV error and S/N for different fringe visibility, derived from Eq. (2). The filled square marks a point for the measured star error. The filled triangle represents the measured iodine error.

Figure 6: Measured RV variation of Aldebaran vs. time over two days at the Palomar 5-m telescope. The large sin-like variation is due to Earth’s acceleration. The measured points are the crosses, which trace the Earth’s motion.
approach. Figure 6 shows the RV curve of Aldebaran over two nights. Apparently, the RV measurements not only trace the diurnal velocity variation each night, but also connect over these two days’ data despite a change of > 400 m/s due to Earth rotation and an image shift as large as 3 pixels in the dispersion direction due to the unstable thermal environment and instrument adjustments (e.g. temperature fluctuations were ~ 4°C in the Palomar Coudé room where the instrument was installed). The residual 1-sigma RV error after we have subtracted the diurnal velocity component is ~ 23 m/s, a factor of two times larger than we achieved at the HET. The larger random error (~ 19 m/s) in the short term (< 1 hr) can be explained as follows: although throughput was considerably higher at Palomar (hence the more frequent data points), the images were significantly aberrated, with visibility varying noticeably across a fringe. This leads to large errors in the curve-fitting accuracy. Since we fed two fiber beams simultaneously to the system, the stellar beam had to be placed off optical axis, which caused higher optical aberration than at the HET. The RV variation over longer than 1 hr may be caused by stellar pulsations and or systematic errors. Previous observing of this star shows RV variations with an amplitude of ~ 200 m/s over a period of 643 days period (Hatzes & Cochran 1993) and ~ 10 m/s over a period of ~ 2 hours (Smith et al. 1987). Nevertheless, future additional observations are required to verify whether the stellar pulsation contributes to our RV measurements.

Our Palomar results also demonstrate that multiple object observing is feasible with the interferometer. Figure 7 shows two adjacent fringe spectra taken simultaneously by our ET and CCD camera. Due to limited resources and time, we were not able to feed two star beams to the ET. Instead we fed one stellar beam and another ThAr lamp beam to the system. Since we only use ~ 70 pixels in the slit direction for covering interference fringes, we can technically cover ~ 15 fringe data from 15 stars simultaneously with the current 1k×1k CCD camera. Further analysis of these data shows that the ThAr fringes can trace instrument drift within ~ 100 m/s over ~ 5 hours. During this time the uncalibrated bulk instrument drift was ~ 2.5 km/s as shown in Figure 8. This is largely...
attributable to 4°C temperature drifts during the observations. Hence, this result illustrates that the ThAr lamp can be used for tracing instrument drift in the interferometer approach. However, future improvements in environment temperature control are needed to further reduce calibration error using the two-fiber calibration technique. A similar calibration technique has demonstrated ~ 5 m/s precision with the echelle approach (Baranne et al. 1996).

A modified version of the ET was used for the engineering run at the KPNO 2.1-m telescope in Aug. 6th – 18th 2002 before we install a permanent one in 2003 for a long-term survey (Figure 9). The old f/10 spectrograph was replaced by an f/7.5 spectrograph. The KPNO 1k×3k back-illuminated CCD with 15 µm pixels was used instead of the old 1k×1k CCD. The wavelength coverage has been increased to 270 Å due to the faster instrument focal ratio and larger detector array. An f/8 telescope beam is fed into a 200 µm fiber, which matches a 2.5 arcsec stellar image. Due to the focal ratio degradation, the output focal ratio of the fiber is f/6, which is converted to f/7.5 to feed the spectrograph. The spectrograph entrance slit width was dialed to about 180 µm, which causes about 30% photon loss at the slit. The FWHM of each absorption line is sampled by 12 pixels. Under 1.5 arcsec seeing conditions, the total instrument throughput including the sky, telescope transmission, fiber loss, instrument and iodine cell transmission and detector quantum efficiency is 3.4%. This was achieved by feeding only one of the two interferometer outputs into the spectrograph. This allows us to routinely observe stars as faint as V = 7.6 magnitude stars during the whole run. Figure 10 shows typical fringe data of eta Cas, a RV standard star (V = 3.5 mag. Cochran 2002 private communications), 51 Peg (V = 5.5 mag.) and HD 209458 (V = 7.6 mag). Although the seeing condition was never better than 1.5 arcsec during the run, we still were able to continually monitor 6 stars (Arcturus, eta Cas, upsilon And, 51 Peg, 31 Aql, and HD 209458) over 8 nights when sky was relatively clear. Since the data format has been largely changed from our previous observations at the HET and Palomar (300 pixels in the slit direction vs. ~ 70 pixels in the HET and Palomar data), we were only able to process part of the
fringe data in a half data format using the existing data analysis program. The Doppler precision for the Eta Cas over three nights is about 10 m/s as shown in Figure 11. The noise seems quite random. The statistical errors from the curve fits to the fringes for Eta Cas, 51 Peg and HD 209458 templates (also half data format) indicate an intrinsic Doppler precision of 6 m/s, 8 m/s and 22 m/s, respectively. These errors are consistent with the theoretical estimated errors based on photon statistics in Eq. (2) (Figure 12). The intrinsic Doppler error for the Arcturus data is about 2 m/s when its S/N is about 4 times higher than Eta Cas, indicating our instrument is probably limited by photon noise.

We have also installed a thermally controlled enclosure for the ET to stabilize the instrument environment at the 2.1m as shown in Figure 9. A heating blanket heats the instrument to about 32°C and is stable within ±0.5°C for 10 days. This is the first time we tried to enclose the whole instrument in a temperature-controlled environment. The CCD drift due to the filling of the liquid nitrogen dominates the whole instrument drift, although this diminishes with time after filling. Future improvement of the LN2 filling is necessary for improving the whole instrument stability.

4. Comparison between this approach and previous interferometer approaches

Our approach is fundamentally different from the previously proposed Holographic Heterodyning Spectroscopy (HHS) for high precision stellar RV measurements based on a variable delay interferometer (e.g. Douglas 1997; Frandsen et al. 1993): in this approach, one or both interferometer mirrors are replaced by a grating to generate rapidly varying optical path difference without moving parts. The resulting interference patterns from different delays are recorded by a detector array and Fourier transformed to a narrow band high-resolution spectrum. These kind of instruments are modified Fourier Transform Spectrographs without scanning, and in principle, they can be used for high precision RV measurements since the PSFs are better defined and more stable than the echelle spectrometers. However, their sensitivity is less than grating spectrometers due to the small bandwidths (~ 30 Å) and the superposition of fringes from different wavelengths (high background noise). The latter hurdle was overcome by using a postdisperser (Frandsen et al. 1993). However, the former is the fundamental limit. In current echelles, ~ 1000 Å wavelength coverage is used for reducing photon noise in RV measurements (e.g. Butler et al. 1996). This results in ~ 6 times higher Doppler precision for echelles than these previous kinds of heterodyned instruments for the same spectral resolution. In comparison, our fixed-delay interferometer approach has a practical bandwidth of ~ 3000 Å limited by the blaze function of the postdisperser (Ge 2002). Therefore, high Doppler precision can be reached through broadband and high S/N observing.
5. All Sky Doppler Surveys for Extra-solar Planets

Observations with the prototype have demonstrated that the fixed-delay interferometer is suitable for multiple object observing and can provide high throughput and high Doppler precision. Multi-object and high throughput Doppler surveys are important since they can significantly speed up the detection of extra-solar planetary systems and also reduce the cost. Currently, only about 4000 solar type stars are being searched by half a dozen telescopes using the echelles. Based on current planet detection rate of 10% of solar type stars, ~400 planets will be discovered in the next ~10 years. These surveys are time-consuming and very costly. This is because current echelles can only measure a single object per exposure, and because only relatively bright stars can be observed since the instrument has low detection efficiency, whereas high photon flux is required for precision measurements. Therefore, in principle, a multiple object RV survey can improve the current situation.

Considering there are not many bright stars in the sky for the measurements, the multiple object survey must include relatively faint stars within the telescope field of view (FOV). Based on our estimation from previous star count surveys in the visible (Bahcall & Soniera 1980) and a dust extinction map (Schlegel et al. 1998), we find there are about a half million stars from A – M types brighter than V = 10 mag., and about 4 millions of stars are brighter than V = 12 mag. (see Table 1 for details). On average, about 100 stars with V magnitude brighter than 12 mag. are within a 1 deg field-of-the-view. Therefore, in order to conduct an efficient all sky survey for extra-solar planets with a multiple object fixed-delay interferometer, we need to reach about V = 12 mag. with a telescope with a wide field of view.

This all sky survey is possible with modern wide field telescopes such as the Sloan 2.5-m and the WIYN 3.5m telescopes. The Sloan has a 7 deg. FOV and the WIYN has a 1 deg. FOV. Since both of the telescopes have moderate telescope aperture size, high throughput becomes critical for reaching high Doppler precision. High throughput can be reached with an optimally designed interferometer. The prototype at the KPNO 2.1-m has already demonstrated good throughput of 3.4% under 1.5 arcsec seeing. In

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>$m_{&lt;10^{th}}$</th>
<th>$m_{&lt;11^{th}}$</th>
<th>$m_{&lt;12^{th}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1-A9</td>
<td>292693</td>
<td>756629</td>
<td>1704211</td>
</tr>
<tr>
<td>F0-F9</td>
<td>183666</td>
<td>559194</td>
<td>1515384</td>
</tr>
<tr>
<td>G0-G9</td>
<td>29864</td>
<td>95083</td>
<td>1309935</td>
</tr>
<tr>
<td>K0-K9</td>
<td>5941</td>
<td>22649</td>
<td>81039</td>
</tr>
<tr>
<td>M0-M9</td>
<td>149</td>
<td>620</td>
<td>2382</td>
</tr>
<tr>
<td><strong>Total counts</strong></td>
<td><strong>512313</strong></td>
<td><strong>1434173</strong></td>
<td><strong>3612950</strong></td>
</tr>
</tbody>
</table>

Table 1. All sky star counts.

<table>
<thead>
<tr>
<th>Components</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope (KPNO 2.1m) 2 mirrors</td>
<td>81%</td>
</tr>
<tr>
<td>Fiber feed at f/5 (2 arcsec, or 100 μm fiber)</td>
<td>50%</td>
</tr>
<tr>
<td>Interferometer (using two outputs)</td>
<td>90%</td>
</tr>
<tr>
<td>VPH grating</td>
<td>85%</td>
</tr>
<tr>
<td>Spectrograph optics (~ 16 surfaces)</td>
<td>85%</td>
</tr>
<tr>
<td>Detector (back-illuminated CCD)</td>
<td>90%</td>
</tr>
<tr>
<td><strong>Total efficiency</strong></td>
<td><strong>24%</strong></td>
</tr>
</tbody>
</table>

Table 2. Total detection efficiency estimation in the proposed new instrument at the KPNO 2.1-m
the future, a factor of 4 times improvement should be achievable, including 2 times in the interferometer transmission by feeding both interferometer outputs to the spectrograph, 1.4 times in the étendu match through updating current spectrograph with a faster spectrograph (e.g., $f/2$ instead of $f/7.5$), and 1.5 times in the spectrograph transmission by using a higher efficiency grating (such as a VPH grating with ~ 85% efficiency instead of current reflection grating with ~ 55% efficiency). A total estimated detection efficiency of ~15% can be expected. Table 2 lists the potential transmission in each of the telescope and instrument optics in the new instrument we are building for the 2.1-m telescope. It appears that ~24% total efficiency is reachable. In reality, considering seeing variation, we may only be able to reach ~15% total efficiency. With this detection efficiency, a Doppler precision of ~15 m/s can be reached for a $V = 12$ mag. star within an hour integration and ~1000 Å wavelength coverage. In principle, most of the stars brighter than $V = 12$ mag. can be surveyed with high Doppler precision for planet candidates at 2 m class wide field telescopes with multi-object RV instrument. The candidate systems can be further studied with a single object high throughput interferometer with higher precision at larger aperture telescopes to look for additional planet members.

In the future, in order to take full advantage of the potential of the multi-object fixed-delay interferometer for all sky surveys for extra-solar planets, we need to simultaneously feed multi-object fiber bundles into three instruments, a near-IR interferometer, a visible interferometer and a near-UV interferometer as shown in Figure 13. This design allows maximal matching of the interferometer sensitivity with the peak of the spectral flux and lines. For instance, a late M type star has about 10 times more flux in the near-IR than in the visible and has many molecular and atomic lines for precision Doppler measurements (Kirkpatrick et al. 1993). Because the line width is very different from early type to very late types, the optical delay will be changed accordingly to minimize Doppler errors. To fully achieve high Doppler precision with this instrument, a large waveband is very important since this will allow the capture of more photons from stars for the measurements (Eq. 4). In the prototype, the Doppler precision is limited by the wavelength coverage and the accuracy of wavelength calibration. A Doppler precision of ~9 m/s has been achieved with a wavelength coverage of ~140 Å and $S/N \sim 120$ per pixel with an $f/10$ spectrometer. The small wavelength coverage is due to the slow optics used for the spectrometer. Future upgrade with faster optics such as $f/2$ instead of $f/10$ in the prototype can increase wavelength coverage by a factor of 5. Therefore, this operation alone can possibly improve Doppler precision from the current ~9 m/s down to ~4 m/s for $S/N \sim 250$ per pixel even if the low visibility iodine source is used as the reference. Doppler precision can be possibly further reduced by using reference sources with higher visibility than the iodine absorption. Our measured fringe visibility for typical Thorium lines in our Palomar data is about 50%, resulting in intrinsic Doppler error well below 1 m/s. Current RV measurements using ThAr calibration in Dr. Mayor’s group have already achieved ~5 m/s precision and with further improvement such as double fiber mode scrambling and vacuum operation, they believe that they can reach ~1 m/s in the

![Figure 13. A schematic layout of a multiple object fixed-delay interferometer for all sky surveys for extra-solar planets. Three interferometer instruments are simultaneously used for monitoring stars from very early types to very late type in the near-UV, visible and near-IR wavelengths.](image-url)
new HARPS high resolution echelle spectrometer (Queloz 2002 private communications; Pepe et al. 2000). We believe we may be able to achieve similar calibration precision by using similar procedures. If this technique works, this two-fiber calibration technique can potentially triple observing efficiency over our current iodine-based technique since there will be no photon loss due to iodine absorption (typical loss by iodine absorption ~ 30-40%) and also since there is no need to create a separate stellar template for each observation. This will be a big plus for the survey.

In conclusion, to have a very successful all sky survey requires capability of observing at least 100 objects, high Doppler precision and high throughput. A wide field telescope with at least three interferometer instruments optimized for near-UV, visible and near-IR wavebands can provide the best sensitivity for early to very late type stars for detecting hundreds of thousands of planets in the near future.

Acknowledgements

The authors are grateful to Larry Ramsey, Don Schneider, Eric Feigelson, Steinn Sigurdsson, Tom Soltysinski, Ron Reynolds, Fred Roesler, Didier Queloz, Harvey Moseley, Bruce Woodgate, Roger Angel, Mike Shao, Chas Beichman, Bill Cochran, Wes Traub, Ed Jenkins and Jim Gunn for useful discussions. We acknowledge support from the HET staff, the Palomar observatory staff and KPNO staff. This work is supported by NASA JPL and Penn State Eberly College of Science. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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