Comparison Studies of DFDI and Echelle Method in the Search of Exoplanets

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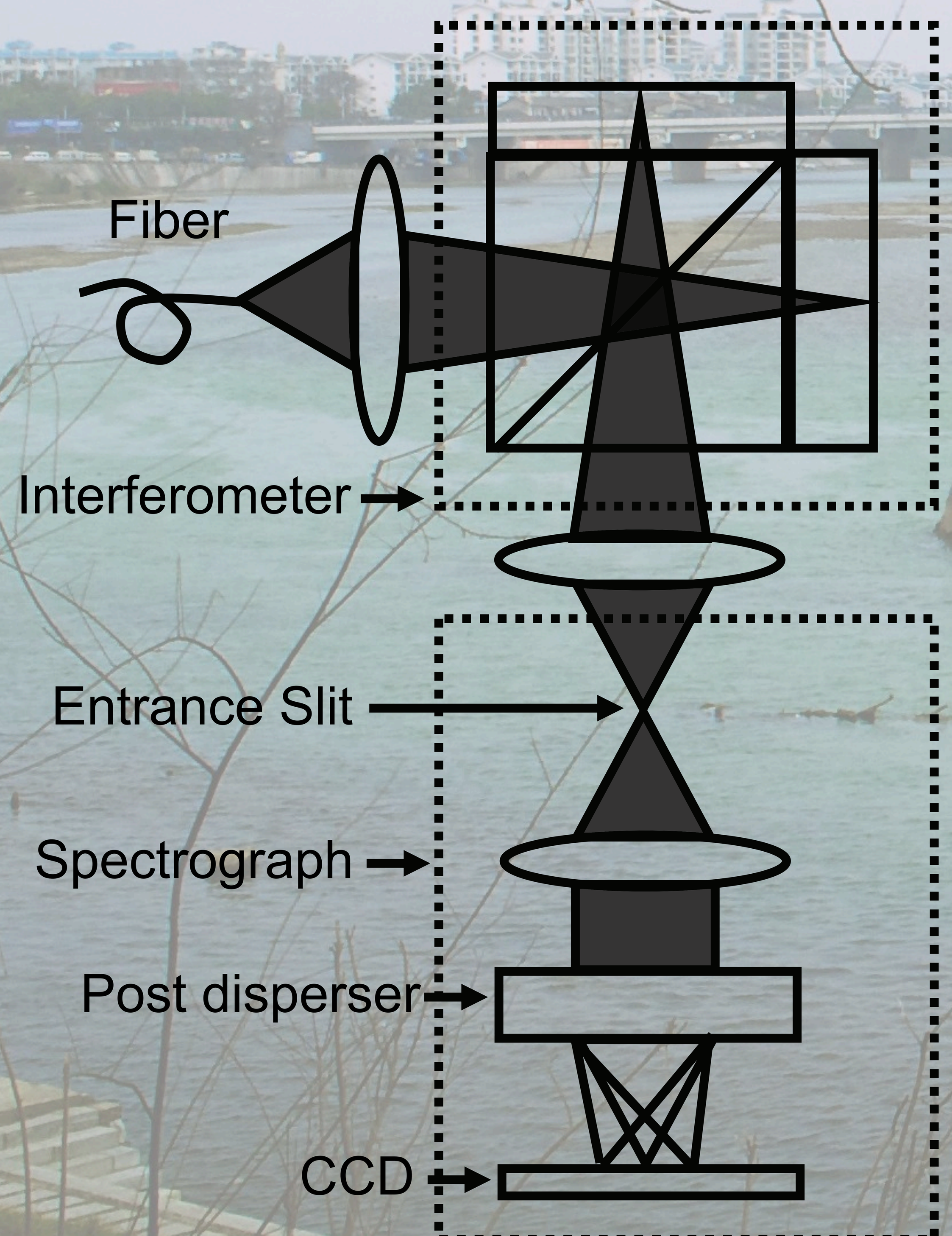
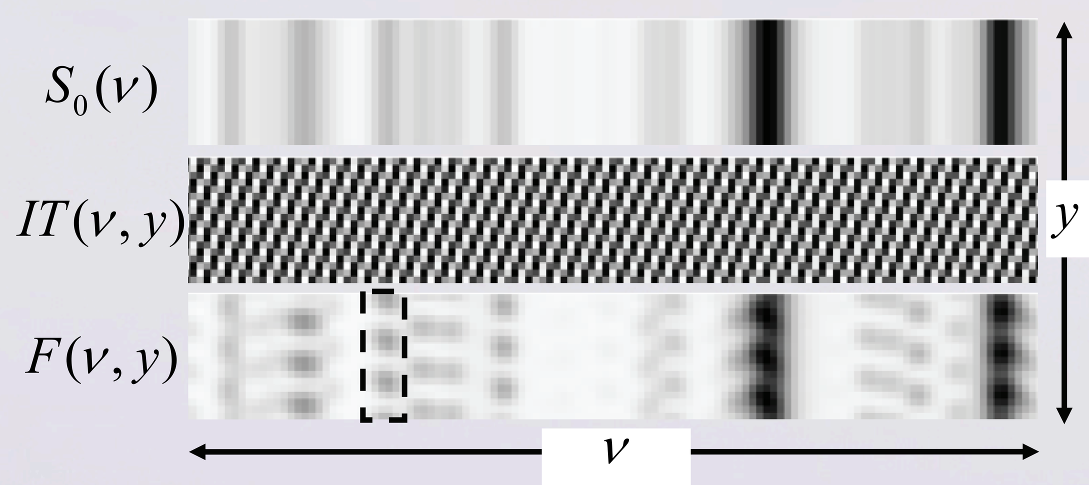
Abstract

We review the principle of the dispersed fixed delay interferometer (DFDI) method and calculate the fundamental photon-limited radial velocity (RV) uncertainty of DFDI. The Q factor is a measure of flux-normalized doppler sensitivity. We compare Q_{DFDI} and Q_{DE}, the Q factors for the conventional direct echelle (DE) method. We find that Q_{DFDI} is a factor of 1.5~4 higher than Q_{DE} at spectral resolution *R* ranging from 5,000 to 20,000. Q_{DFDI} and Q_{DE} converge at very high *R* (*R* > 100,000). We also find that DFDI is more advantageous to DE if given a limited detector resource. We simulate the performance of the InfraRed Exoplanet Tracker (IR-ET), which is a DFDI mode of the IRET/FIRST instrument that will be installed at the 3.5 m telescope of Apache Point Observatory in the winter of 2011. The predicted photon-limited RV uncertainty suggests that IR-ET is capable of detecting earth-like exoplanets in habitable zone around bright M dwarfs.

Principle of DFDI

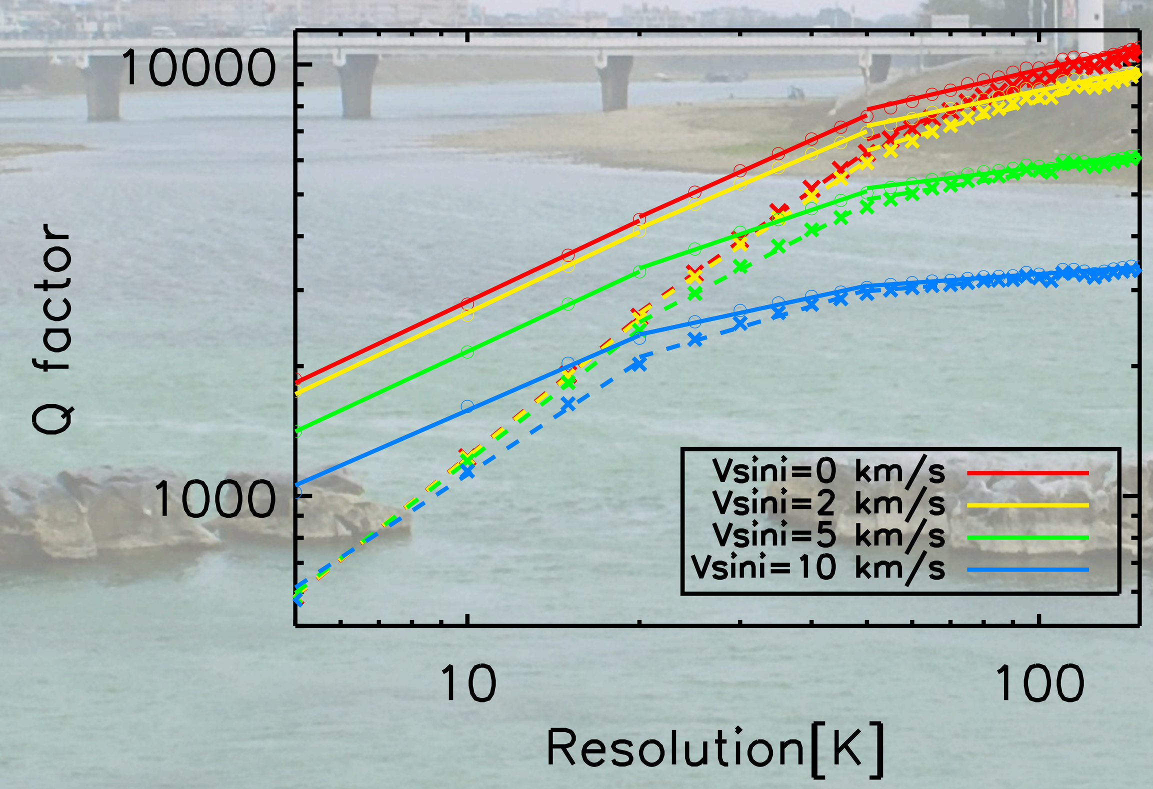


The key difference between DFDI and DE is the insertion of interferometer, the fringe density of which is comparable to the absorption line density of an intrinsic stellar spectrum.



Instead of seeing a stellar spectrum, we see a fringing spectrum, which is a result of superimposing the interferometer combs atop an intrinsic stellar spectrum. RV is measured by monitoring the phase shift of each wavelength channel.

Comparison of DFDI and Echelle Method



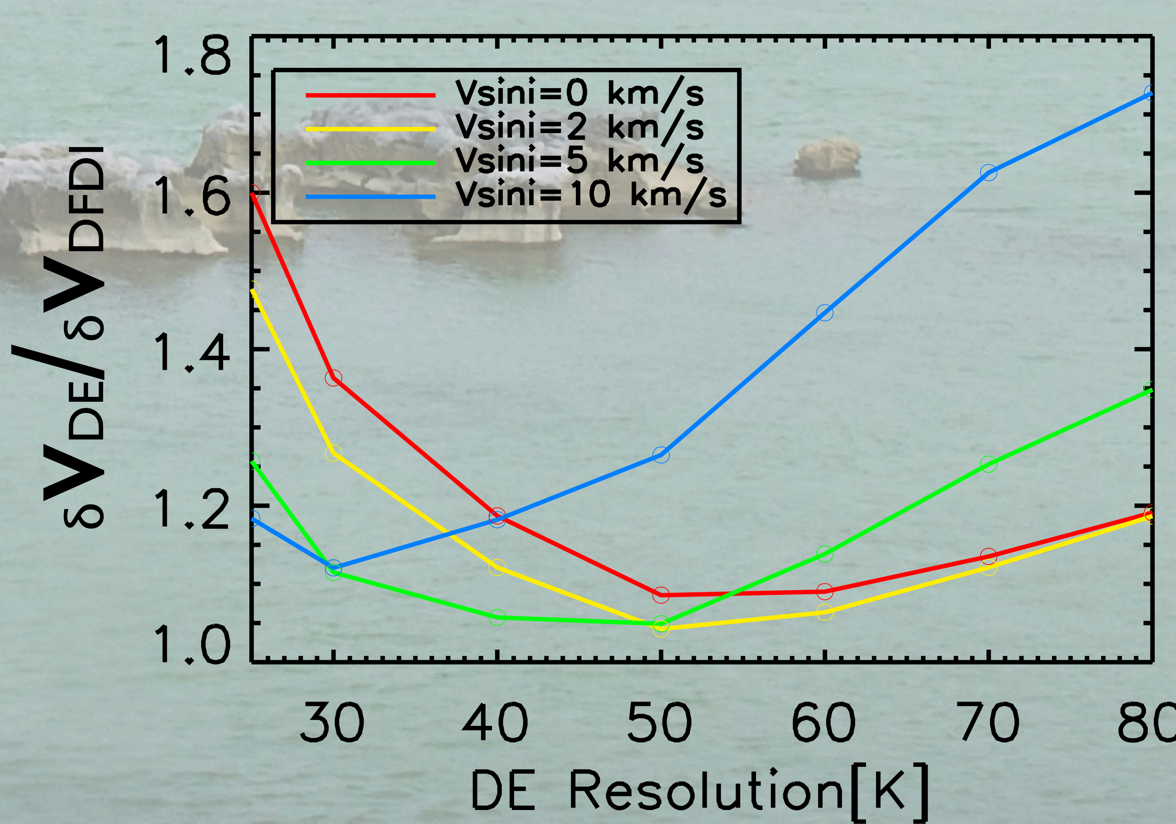
A spectrograph with infinitely high resolution would be able to extract all the RV information contained in a stellar spectrum. On the other hand, spectral response function drops at the high frequency end with finite *R*, which makes it impossible to extract all the RV information. In the wavelength coverage from 800 nm to 1350 nm, we calculate Q factors for stellar spectra (T=2800 K) with Vsini of 0, 2, 5 and 10 km/s at different *R* (5,000 to 150,000 with a step of 5,000) in order to investigate the dependence of Q on *R* (solid line-D_{DFDI}, dashed line-D_{DE}). We find that we are able to extract more RV information (higher Q factor) as *R* increases. Q factors for DFDI and DE converge at very high *R* (*R* > 100,000). For very slow rotators (0 km/s ≤ Vsini ≤ 2 km/s), the advantage of DFDI over DE is obvious at low and medium *R* (5,000 to 20,000). The improvement of DFDI is ~3.5 times (*R*=5,000), ~2.5 times (*R*=10,000) and ~1.6 times (*R*=20,000) respectively. In other words, optimized DFDI with R of 5,000, 10,000 and 20,000 is equivalent to DE with *R* of 17500, 25000 and 32000 respectively in terms doppler sensitivity. The improvement of DFDI at *R* from 20,000 to 50,000 is not as noticeable as low R range. However, DE has to increase exposure time by a factor of at least 1.5 times in order to reach the same RV precision as DFDI assuming the same instrument throughput. The difference between DFDI and DE becomes negligible when *R* is over 100,000. For relatively faster rotators (5 km/s ≤ V sin i ≤ 10 km/s), The improvement brought by DFDI is less obvious than it is for very slow rotators.

Comparison With the Same CCD Detector

$$\Delta\lambda = \frac{N_{\text{pixel}}}{P_{\text{order}}} \cdot \frac{\lambda_0}{R \cdot \varepsilon}$$

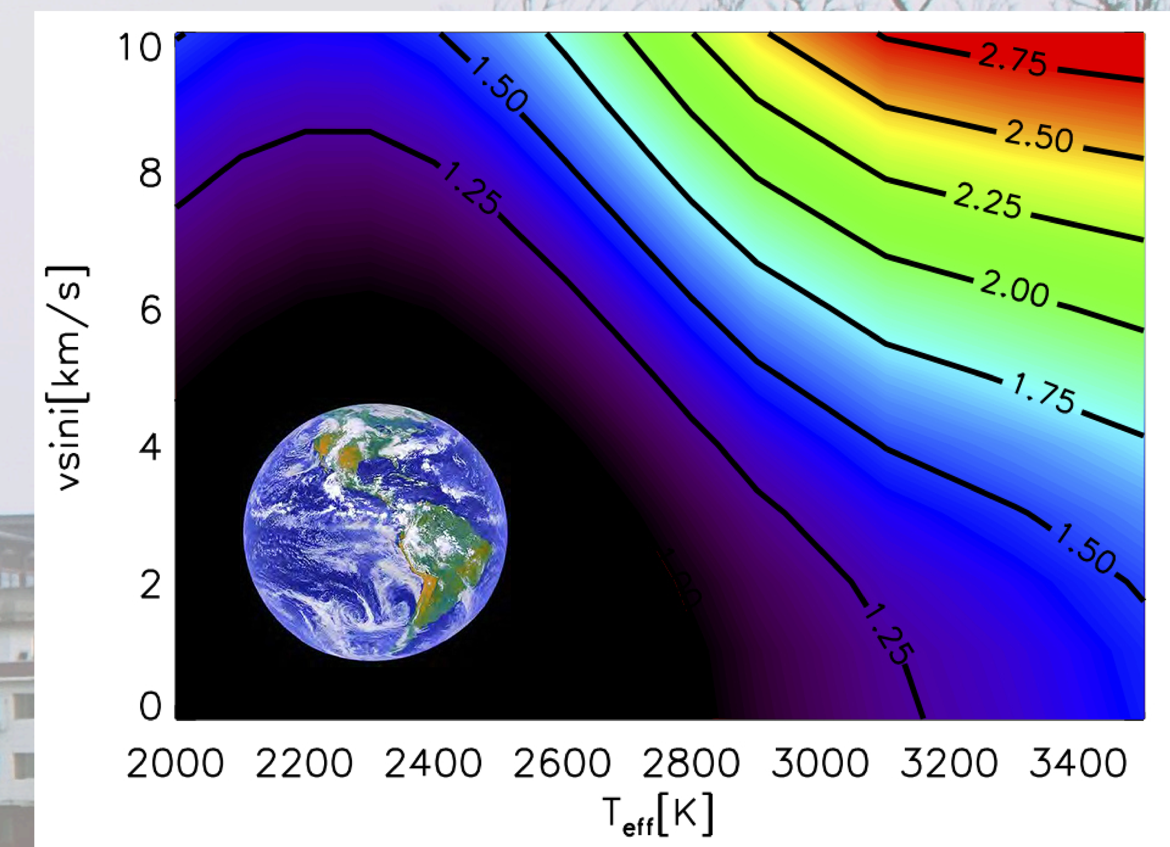
where N_{pixel} is the number of pixels available on a detector, λ_0 is the central wavelength, *R* is the spectral resolution, ε is the number of pixels per resolution element (RE), and P_{order} is the number of pixels sampling one spectral order including the space between orders.

R	$\Delta\lambda$ (μm)	$\lambda_{min} \sim \lambda_{max}$ (μm)
25,000	0.48	0.80~1.28
30,000	0.40	0.80~1.20
40,000	0.30	0.85~1.15
50,000	0.24	0.88~1.12
60,000	0.20	0.90~1.11
70,000	0.17	0.91~1.08
80,000	0.15	0.92~1.07



At a R_{DE} higher than R_{DFDI} of 22,000 (i.e., the spectral resolution for IR-ET), for a given number of pixels on the detector, $\Delta\lambda_{DFDI}$ is larger than $\Delta\lambda_{DE}$. In addtion to the advantage of Q factor for DFDI, the photon flux of DFDI is higher than DE due to the larger wavelength coverage. Consequently, we see in the figure above that DFDI method reaches smaller photon-limited RV uncertainty than DE. The minimum of $\delta v_{DE}/\delta v_{DFDI}$ is dependent on Vsini. The ratio reaches a minimum (i.e., δv_{DE} reaches minimum) around an *R* of 50,000 for slow rotators (Vsini ≤ 5 km/s). It increases at the low *R* end because of the advantage of Q factor for DFDI. On the contrary, the ratio increases at the high *R* end because of fewer photons for DE (see table above). For fast rotators (i.e.,Vsini=10 km/s), the ratio reaches a minimum around *R* of 30,000.

Earth-like Planet Search Around M Dwarfs



Predicted photon-limited RV uncertainty contours (in m/s) for IR-ET. The assumption in calculation includes: 1) t_{exp} = 30 min; 2) J = 9; 3) instrument throughput in J band, η, is 15%. The S/N per pixel at J band is ~80.

Name	m_J	T_{eff} (K)	$V \sin i^a$ ($\text{km} \cdot \text{s}^{-1}$)	K ($\text{m} \cdot \text{s}^{-1}$)	$\delta v_{rms,S}{}^b$ ($\text{m} \cdot \text{s}^{-1}$)	$K_{\text{HZ}}{}^c$ ($\text{m} \cdot \text{s}^{-1}$)
GJ 1214 b[1]	9.75	3000	2	12	2.4	1.0
GJ 176 b[2]	6.46	3500	1	4.1	0.58	0.57
GJ 179 b[3]	7.81	3400	1	26	1.05	0.66
GJ 436 b[4]	6.9	3684[d]	1	18.7	0.71	0.59
HIP 57050 b[5]	7.61	3190	1	38	0.91	0.68

Note. — a: $V \sin i$ is assumed to be 1 $\text{km} \cdot \text{s}^{-1}$ if otherwise specified in references; b: the fundamental photon-limited RV uncertainty; c: velocity semi-amplitude if there is a habitable earth-like planet locating at 0.05 AU from host star; d: we assume T_{eff} to be 3500K because we do not have synthetic stellar spectrum with T_{eff} higher than 3500K.

References. — 1, Charbonneau et al. (2009); 2, Forveille et al. (2009); 3, Howard et al. (2010); 4, Butler et al. (2004); 5, Haghighipour et al. (2010)

As of April 2011, there were only five M dwarf exoplanets discovered in the northern hemisphere. We compare the velocity semi-amplitude K of these exoplanets and RV uncertainty predicted for IR-ET (see the table above). All of them would be detectable by IR-ET under photon-limited conditions. Therefore, IR-ET is a suitable instrument conducting follow-up RV measurement. We also compare the velocity semi-amplitude, K_{HZ}, if there is an Earth-mass planet located within the habitable zone (0.05 AU away from the host star) and the IR-ET photon-noise detection limit. We find that the RV uncertainty of IR-ET is slightly larger than K_{HZ}. However, it should be able to discover Earth-like exoplanets in HZ around bright stars under photon-limited condition.