Hunting for Earth-Mass Exo-Planets with the Dispersed Fourier Transform Spectrometer

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1.0 Abstract

We propose to undertake a program of radial-velocity (RV) measurement tailored to finding several dozen Earth-mass exo-planets orbiting nearby stars. While our primary goal is to find Earth-mass exo-planets, we will also detect more massive planets. Our survey will place constraints on the low-mass part of the exo-planet distribution function. In addition to being scientifically important, the distribution function of Earth-mass exo-planets will help shape our perception of mankind's place in the Universe. Our survey will also provide a target list for future (space-based) programs designed to find and characterize Earth-mass planets (EMPs). While NASA's KEPLER will determine the frequency of EMPs (η_{earth}) around distant stars, our program will yield a list of nearby stars that can be observed by planet-characterization missions such as NASA's SIM and TPF, and ESA's DARWIN. We propose to use the dispersed Fourier Transform Spectrometer (dFTS) that has recently been developed at the US Naval Observatory (Hajian *et al.* 2007). The interferometric nature of this instrument opens new possibilities for high precision velocimetry not available to echelle-based systems. The dFTS uses a frequency-stabilized laser to determine an extremely accurate wavelength scale. Our experience with the prototype instrument indicates that the current systematic-error floor of a few m/s can be lowered to the cm/s level required for EMP detection.

2.0 Introduction

The first extra-solar planet (51 Peg b) was discovered via the RV method in 1995 (Mayor & Queloz 1995). 51 Peg b and many of the subsequent discoveries are located very close to their parent stars (e.g., see Butler *et al.* 2006 for a review). The then-current theories of planet formation did not allow for massive, close-in planets, or “hot Jupiters." Currently, these systems are thought to have formed at larger distances, after which they “migrated" towards the star due to interactions with the proto-planetary disk (e.g., Lin & Papaloizou 1986; Lin, Bodenheimer, & Richardson 1996; Papaloizou & Terquem 2006, and references therein). Three EMPs were discovered via the pulsar-timing technique (Wolszczan & Frail 1992), while one has been found in a micro-lensing experiment (Beaulieu *et al.* 2006). While ground-based planetary-transit surveys are unlikely to yield EMPs (Gillon *et al.* 2006), they *can* be discovered via space-based transit photometry. The COROT mission can find close-in EMPs if they exist (Borde, Rouan, & Leger 2003), while KEPLER is designed to yield about 50 earth-mass planets in earth-like orbits. JWST can accurately characterize any detected transiting planet down to Uranus/Neptune sized objects (Gardner *et al.* 2006).

The expected RV signal for EMPs is quite small; our home planet induces a RV signal of about 9 cm/s onto the Sun. A signal of 36 cm/s would be expected if the well-known “hot Jupiter" τ Boo b would have a one Earth-mass (M_{earth}) planet instead of its detected 4.1 Jupiter mass (M_J) planet. The current observational RV limit is about 1 m/s, hence, the detection of Earth-mass planets requires significant instrumental improvements. In addition, the stars also exhibit a significant amount of RV jitter that needs to be overcome (see Section 4) by any program that detects EMPs via velocimetry.

Members of the European HARPS consortium are actively investigating how to push echelle velocimetry technology towards the cm/s accuracy regime for implementation on the ELT (Lovis *et al.* 2006). However, they are primarily motivated by cosmology, where, with an accuracy at the cm/s level, it is possible to observe redshift changes due to the changing Hubble constant and differentiate between various cosmological models (Sandage 1962).

An alternative way to find *nearby* earth-mass planets is via high-resolution observations of individual stars, either interferometrically (SIM, TPF-I, DARWIN) or by employing high-resolution, high-dynamic range imaging techniques (TPF-C). The driving force behind these missions is to characterize the physical conditions these EMPs and, eventually, to aid in the search for life.

One problem with TPF and DARWIN is that they don't know where to look, and can only observe a very limited number of targets. Therefore, EMPs may be missed by these missions. SIM is the only planned survey mission that can observe relatively large numbers (hundreds) of stars with an accuracy that can reveal EMPs (e.g., Catanzarite *et al.* 2006; Marcy *et al.* 2005; Sozzetti 2005). Hence, SIM can provide target lists for TPF and DARWIN that are significantly “enriched" with potential EMPs (Unwin *et al.* 2007; Catanzarite *et al.* 2006). Unfortunately, when multiple companions are present, SIM data will not provide highly significant detections, due to the fact that for such systems, the same data will need to constrain the orbits of multiple companions (Ford 2006). Development of an earth-based instrument for performing surveys of candidate target lists seems a prudent and useful allocation of resources given the huge funding requirements for the above-mentioned space-based programs.

3.0 Radial Velocity Surveys

It is well-known that the RV technique is more efficient for short periods (**P**) than the astrometric method, while long-period companions are more easily revealed by astrometry. According to Ford (2006), the transition between the two methods occurs roughly at period:

$$P_t \approx 5 \, \frac{\sin i}{0.5} \, \frac{D}{10\,pc} \, \frac{\sigma_{SIM}}{1\,\mu as} \, \frac{3\,cm/s}{\sigma_{RV}} \qquad [\mathrm{yr}] \ ,$$

where **D** is the distance, **i** the inclination of the orbit, and $\boldsymbol{\sigma}_{\mathbf{SIM}}$ and $\boldsymbol{\sigma}_{\mathbf{RV}}$ are the astrometric and radial velocity accuracies, respectively. This Equation is independent of stellar and planetary mass. In the transition regime with $0.5\ P_t < \mathbf{P} < 2\ P_t$, the addition of radial velocity data to astrometric data (or vice versa) has the effect of increasing the accuracy by about $1/\sqrt{2}$ (Eisner & Kulkarni 2002). However, as pointed out by Ford (2006), the combination of astrometric and RV data is much more important when multiple planets are present. In that case, the RV data mostly constrains the orbit of the short period companion, while the astrometry does so for the long-period object. Note that Ford (2006) considered the case of $\boldsymbol{\sigma}_{\mathbf{RV}} \sim 3$ m/s.

This Equation indicates that if we are interested in looking for EMPs in the “habitable zone," where $0.5 \le \mathbf{P} \le 2$ years, an RV survey with $\boldsymbol{\sigma}_{\mathbf{RV}} \sim 3$ cm/s is already much more efficient than a SIM survey (for sin(**i**) = 0.5 and **D** = 10 pc). For an RV survey to contribute about equally to a SIM survey for $\mathbf{P} = P_t = 1$ yr, we need $\boldsymbol{\sigma}_{\mathbf{RV}} \sim 15$ cm/s. Thus, for 15 cm/s < $\boldsymbol{\sigma}_{\mathbf{RV}}$ < 5 m/s, RV data would significantly support SIM data.

4.0 Capabilities and Astrophysical Limitations

Based on long-term observations of the Sun, it is generally assumed that the intrinsic stellar RV variability is of order 5 m/s (Jimenez *et al.* 1996; Deming *et al.* 1987; McMillan *et al.* 1993). This knowledge has perhaps dampened the drive towards more highly accurate spectrographs. The current accuracies for the most advanced instruments are about 1 m/s for HARPS and HIRES. On the other hand, “seismology" arguments indicate that longer integration times would smooth-out the RV noise. For example, Melo *et al.* (2007) find RV residuals of only 40 cm/s if they “average" data over a time span of several hours. For comparison, their unaveraged data (typically 15 minute exposures) yielded residuals of 3 m/s. Careful analysis methods are being successfully applied to photometric data, significantly suppressing photometric jitter due to stellar oscillations (Solanki *et al.* 2001). It is likely that similar methods can be used to reduce RV jitter.

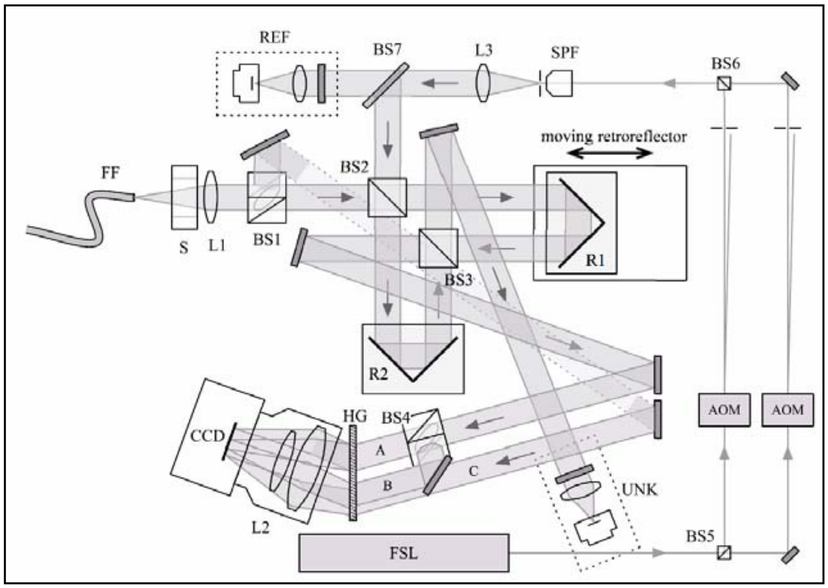

Figure 1: A schematic drawing of dFTS1. Starlight enters dFTS1 via the fiber feed (FF), goes through the Michelson interferometer (polarizing beamsplitters BS2 and BS3, retroreflectors R1 and R2), and is dispersed by grating HG before being detected by the CCD. The metrology system utilizes a frequency-stabilized laser (FSL) which follows the same path through the interferometer as the starlight. More details can be found in Hajian *et al.* (2007).

Another possible way to mitigate convective jitter is to focus on the relative stability of the steep flanks of violet lines. The plausibility of this approach was demonstrated by McMillan *et al.* (1993, 1994) as part of a search for exo-planets. While Deming and Plymate (1994) observed a variation of apparent RV during the solar cycle by observing lines at 2.3 microns, McMillan *et al.* (1993) established a new upper limit on the variability of the RV of the Sun as measured from the steep flanks of photospheric absorption lines in violet light. McMillan *et al.* (1994) saw no variation in the RV of ξ Boo A using the flanks of violet lines. Toner & Gray (1988), observing in the red, saw a large periodic RV variation due to a starspot.

We conclude that substantial improvements can be achieved in the field of RV jitter-reduction, once the data is accurate enough to probe the sub-m/s domain. The dFTS instrumental architecture lends itself to these RV jitter-mitigation techniques, particularly the availability of a blue bandpass, knowledge of the LSF, and the ability to select specific wavenumbers for spectral reconstruction that isolate the line flanks.

5.0 Instrument

Over the past decade, we have developed the dispersed Fourier Transform Spectrometer (dFTS) at the US Naval Observatory (Hajian *et al.* 2007). We modified the traditional FTS (Michelson 1891, 1892) by including a grating (Nordgren & Hajian 1999; Hajian 1998) that boosts the throughput by several orders of magnitude, *and* allows for a much coarser sampling of the interferogram. The combination in series of a grating with a traditional FTS improves the sensitivity of the ensemble by the resolving power of the grating. This is simply a reflection of the well-known fact that interferometers are most sensitive when exposed to narrowband radiation. By using a grating to divide a broad optical bandpass into juxtaposed narrowband segments, the interferometer experiences a massive sensitivity increase. The result is that the current dFTS obtains excellent spectra and velocities for 6th magnitude stars on a 25" telescope, while a traditional FTS needs big telescopes to observe the brightest objects.

We present a schematic layout of our first prototype instrument, dFTS1, in Figure 1. With our prototype instrument we have been able to achieve photon-limited stellar observations, while our *long-term monitoring of ThAr spectra indicate an instrumental stability of about 3 m/s*. This stability is achieved via a full-aperture metrology system that is coincident with the path that the stellar (or ThAr) photons travel through the delay lines. The metrology system uses a frequency-stabilized HeNe laser to precisely measure delays. Accurately determined delays result in an accurate and precise wavenumber scale on our dFTS, and our spectral reconstruction algorithm permits us to specify which wavenumbers are to be reconstructed in the spectral solution.

Because of our combined interferometer and metrology design, dFTS technology could be much more stable than traditional echelle-based spectrometers. Path length differences from changes in the index of refraction of air, vibrations, thermal drift, and optical imperfections can all be monitored by the metrology laser and applied to the starlight beam. In addition, the instrumental line-spread-function is known *a priori* to a very high level of precision from the delay sampling. All of these advantages are uniquely available to interferometers.

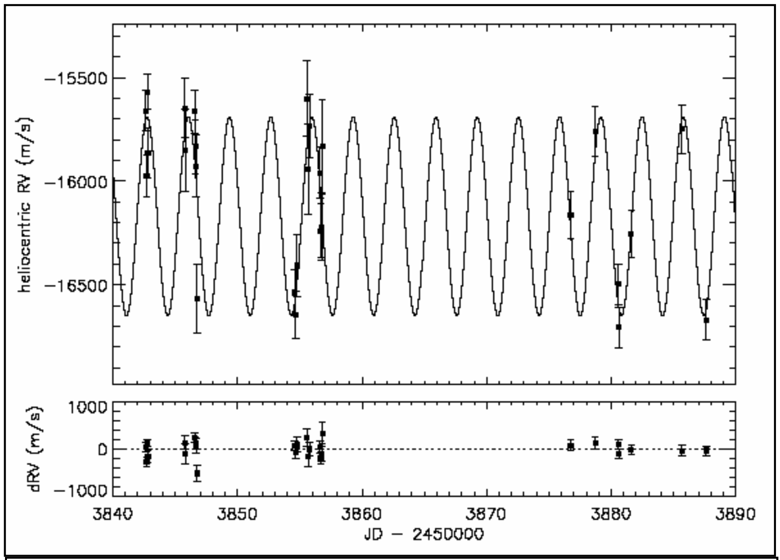

Figure 2: The radial velocity of τ Boo as a function of time. The star τ Boo has a known extrasolar planet companion responsible for the stellar radial velocity variations. The dFTS was upgraded near JD 2453870, as reflected by the smaller residuals afterwards. The solid curve is the best-fit orbit to our radial velocity data.

Our instrument also compares very favorably with the Externally Dispersed Interferometer (Erskine & Ge 2000) and the ``Extra-Solar Planet Tracker" (ET) implementation thereof (Ge *et al.* 2006) because they rely on an iodine cell for velocity calibration. The latter group reports a stability of 13 m/s over two months: about 4x worse than our year-long stability with dFTS1.

The original prototype dFTS1 has been operating for the past 2 years on the Clay Center Observatory (CCO) 25" telescope at the Dexter and Southfield Schools in Brookline, MA. The design, construction, and observational results from this simple prototype are published in Hajian *et al.* (2007), and include observations of several stellar binary and exo-planet systems. An example of the data showing the planet around τ Boo is shown in Figure 2.

We have recently completed the assembly of a more capable instrument, known as dFTS2. This device is intended for use with a larger aperture telescope. We have already increased the throughput of dFTS2 as compared to dFTS1 by a factor of 4.6 by implementing an image slicer, and can also achieve an additional factor of 4-6 by replacing a commercial SLR camera lens with a custom optic. Other, more complex improvements are also possible. An image of dFTS2 is shown in Figure 3, and an example of data from dFTS2 is shown in Figure 4. We note that the entire optomechanical configuration for dFTS2 (excluding 2 control computers, a lock-in amplifier, and small power supplies) occupies an area of 2.5' x 2' and a height of less than 1'. We expect to deploy dFTS2 to the CCO 25" telescope in early May, and then to the USNO Flagstaff 61" telescope during the Summer of 2007.

6.0 Instrument Improvements

To be able to detect EMPs, the stability of our instrument needs to be improved by a factor of at least ten. This can be accomplished in several ways. Our current laser stabilization system is accurate to ~ 1 MHz (or 0.6 m/s), while commercially available modern systems can now reach ~ 12.5 kHz by locking onto specific narrow iodine lines (e.g. Winters Electro-Optical, Inc. 2007, M100 or M200). Upgrading to these modern systems would bring the long-term stability of our dFTS system to 0.75 cm/s, substantially below the requirement for the detection of Earth-mass exo-planets. However, heterodyne systems such as our metrology system typically exhibit cyclic bias features that can limit the precision of the resulting metrology data. We have been investigating techniques for detecting and removing the cyclic bias from metrology data. Although we have achieved significant success in this area, more work is required before we can claim a working solution. Nevertheless, our initial (unfunded) efforts suggest that the cyclic term can be reduced by a factor of ~ 100.

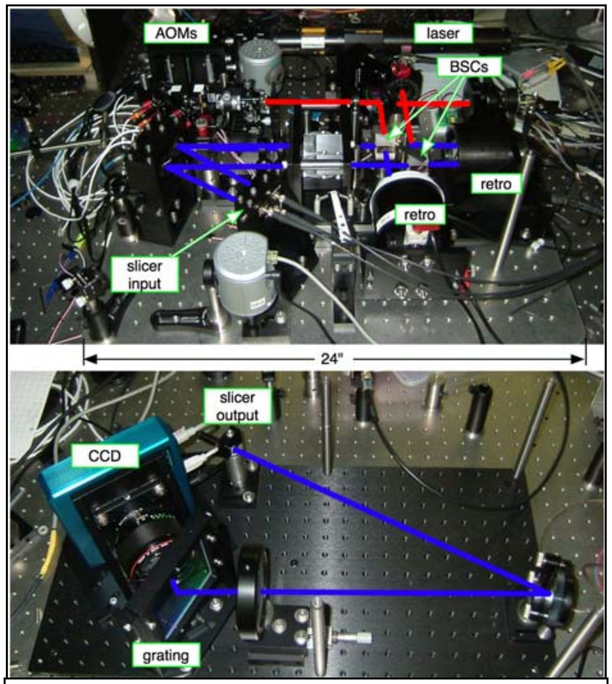

Figure 3: An image of the front end (top) and backend (bottom) of dFTS2.

Because of its small size (a few cubic feet) and weight, the dFTS can be more easily incorporated in a space mission. The small point-spread function of space-based implementations allow for a very significant gain in the throughput and efficiency of dFTS-based velocimeters. It is also important to note that both dFTS1 and dFTS2 operate at significantly shorter wavelengths then many other planet-hunting spectrometers. By observing in the 430-580 nm passband, the dFTS is capable of taking advantage of the much higher line density from late-type stars in this portion of the spectrum as compared to wavelengths longward of ~ 520 nm. For a space-based platform, even bluer wavelengths become accessible.

7.0 Development Plan and Conclusions

There are several relevant conclusions from this white paper. First, the dFTS architecture lends itself to very high precision RV determination. The dFTS has a laser metrology system that can be upgraded with an iodine-stabilized HeNe laser to provide the potential for sub cm/s velocimetry. Knowledge of the instrumental line-spread function *a priori* is also a major advantage. To realize these small velocity uncertainties, the cyclic error must be suppressed and/or removed. We have had good success by taking advantage of the way in which dFTS data is recorded, but this has never been part of a funded program.

The dFTS also has significant potential applications in space. In this environment, the versatile and configurable spectral resolution and modest space and weight requirements of the dFTS are major advantages over any competing technology. The increase in sensitivity as compared to the conventional FTS makes numerous astrophysical targets observable. In addition, the small size of diffraction-limited spots as compared to seeing limited spots (for large

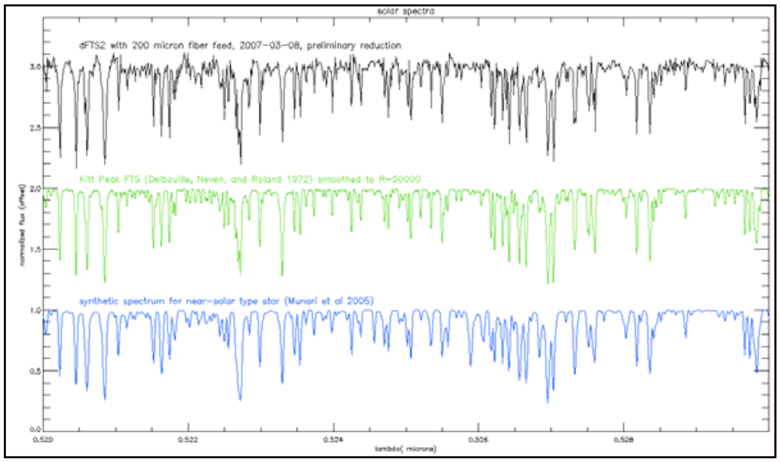

Figure 4: The upper plot shows a spectrum with R = 50,000 from a short integration using dFTS2 fed by a bare fiber pointed at the solar disk. The middle plot shows the equivalent spectral region from the Kitt Peak FTS. The bottom plot shows a model solar spectrum. The multiple deficiencies in the model atmosphere (e.g. 525.8 nm) reflect our lack of understanding of the solar physics.

apertures) means that the grating spectrometer within the dFTS will provide high spectral resolution. This translates into an increase in sensitivity for the dFTS (narrower bandpasses are "dispersed" by the interferometer with higher sensitivity). Finally, the dFTS bandpass is not limited by the location of lines from an absorption cell. Echelles with iodine-cells are limited to observations in the red. We operate the dFTS in the blue where absorption lines from late-type stars are denser than in the red. (In space, the bandpass can be pushed into the UV to further increase the line density.) It may be possible to defeat the astrophysical noise limitation imposed by stellar surface convection by integrating over convective cycles (Melo *et al.* 2007). There is also evidence that obtaining spectra at blue wavelengths and reconstructing the spectral intensities on the steep flanks of absorption lines (only possible with an interferometer) can further suppress RV jitter from convective cycles (McMillan 1993, 1994).

We want to implement a project with our dFTS2 and test it on small-to-midsized telescopes. However, so as to fully realize the potential of the dFTS for EMP detection, we need to observe with much larger apertures and commence a fully funded development and observation program, including construction of a new dFTS incorporating all the stability improvements previously described. The associated cost would be of order a few million dollars. Given our high probability of success, this project has a high cost/benefit analysis as compared to expensive, space-based programs for EMP detection. Following the example of Melo *et al.* (2007), stellar integrations would be conducted lasting several hours each, permitting up to ~ 3 observations per night. Since we want to be able to detect EMPs with periods between 0.5 and 2 years, we need to observe our targets on a ≥ 4-m class telescope at least four times per year. Allowing for clear weather 75% of the time, we can monitor more than 200 stars if 100% of the telescope time is devoted to this project. Then, if $\eta_{\mathrm{earth}} \sim 0.1$, we could discover ~ 20 earth-mass planets in about five years (20 total observations/star). Significant community support would be needed to gain full-time access to a 4-m telescope, but we feel that exploration of the EMP regime warrants this level of resource commitment.

We conclude that an alternative approach to EMP detection using interferometric spectrographs, such as the dFTS, has merit and should be supported.

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