NEAT: a Microarcsec Astrometric Telescope

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Abstract

NEAT, Nearby Exo-Earth Astrometric Telescope is a medium-small telescope ~ 1m in diameter that is designed to make ultra precise < 1 uas (microarcsec) astrometric measurements of nearby stars in a ~ 1hr observation. Four major error sources prevent normal space telescopes from obtaining accuracies close to 1 uas. Even with a small 1m telescope, photon noise is usually not a problem for the bright nearby target stars. But in general, the reference stars are much fainter. Typically a field of view of ~0.5 deg dia is needed to obtain enough bright reference stars. The NEAT concept uses a very simple but unusual design to avoid optically induced astrometric errors. The third source of error is the accuracy and stability of the focal plane. A 1uas error over a ~2000 arcsec field of view implies the focal plane is accurate or at least stable to 5 parts in 10^{10} over the lifetime of the mission (~5yrs). The 4^{th} class of error has to do with our knowledge of the PSF and how that PSF is sampled by an imperfect detector. A Nyquist sampled focal plane would have > 2 pixels per λ/D, and centroiding to 1uas means centroiding to 10^{-5} pixels. This paper describes the mission concept, and an overview of the technology needed to perform 1uas astrometry with a small telescope, and how we overcome problems 1 and 2. A companion paper will describe the technical progress we've made in solving problems 3 and 4.

1. Introduction

The search for Earth like planets remains a challenging goal for exo-planet researchers. There are many ways to detect exo-planets, around nearby stars. Radial velocity, transit, direct imaging (coronagraphy or nulling interferometry) and micro-lensing are other approaches. After finding the planets, we will eventually want to measure the spectra of the planet's atmosphere to search for biomarkers in the atmosphere. To do this, the exo-Earths have to be nearby. That leaves radial velocity, direct imaging, and astrometry as the three remaining techniques. Radial velocity and astrometry are indirect detection techniques that measure the reflex motion of the star due to the planet orbiting it. The ultimate limitation of RV and astrometry is the noise due to stellar activity. For a planet in a 1 year orbit, around a solar like star, a feature on the surface of the star will produce an error or bias in both RV and astrometry. But compared to the signature of an Exo-Earth in a 1yr orbit, the RV noise is ~12 times larger than the astrometric noise.

Our goal is to achieve 1 uas accuracy in a 1 hour observation. This level of accuracy in 1 hour will enable a 5 year mission to search down to a 1 Earth mass planet in the middle of the habitable zone around more than 100 nearby stars. In the following sections, we discuss in order, the science return of a mission like NEAT, a description of major noise and error sources and how they can be overcome. We start with a discussion of photon noise, which defines the parameters of the mission followed by the systematic errors that in practice have limited astrometry from space telescopes to accuracies many orders of magnitude worse that the photon limit.

2 Exoplanet Science and Photon Limited Accuracy

The photon limited accuracy of centroiding a stellar image is well known to be err = width/(2*sqrt(N)) where width is the width of the diffraction limited image and N is the total number of detected photons. In searching for planets around nearby solar like stars, we know that all of the target stars are moderately bright because they are nearby. Photon noise in astrometric measurements for exo-Earth detection is not limited by photon noise from the target star but photon noise from the much fainter reference stars. The larger the field of view of the telescope, on average, the brighter the reference stars will be. The density of stars (# stars per square degree) versus magnitude from Allen's AQ4 provides the contents of table 1.

#ref stars	5	6	7	10	100	
phot noise	0.73	0.71	0.69	0.65	0.52	uas
faintest	11	11	11	12	14	mag

The table is for a telescope field of view of 0.6 degree diameter. If the reference frame is defined by the brightest 5 stars in the field, the faintest star will be 11 mag and the photon noise limited precision of the reference frame would be 0.73 uas in a 1 hour observation. If we use the 100 brightest stars in a 0.6 deg diameter field, the faintest star would be 14 mag and the photon noise limited precision of the frame would be 0.52 uas. From a photon noise point of view we get most of our accuracy from the ~10 brightest stars. Since the stars are randomly located on the sky, on average, the photon limited accuracy of the reference frame will be proportional to the diameter of the field of view.

Similarly, the photon noise in astrometric measurements will decrease as $1/D^2$ where D is the diameter of the telescope. A telescope with twice the diameter will collect four times as many photons, resulting in a 2X increase in photon limited accuracy. At the same time the width of the diffraction spot will decrease by 2X, resulting in a total 4X increase in photon limited accuracy. With lower photon noise, one can search a larger number of stars for Earth-like planets. Table 2 shows the accuracy of various sized telescopes, and the number nearby stars that can be searched if the search sensitivity was set to a 1.0 M_{earth} planet in a 1 AU orbit or alternatively 1.4 M_{earth}.

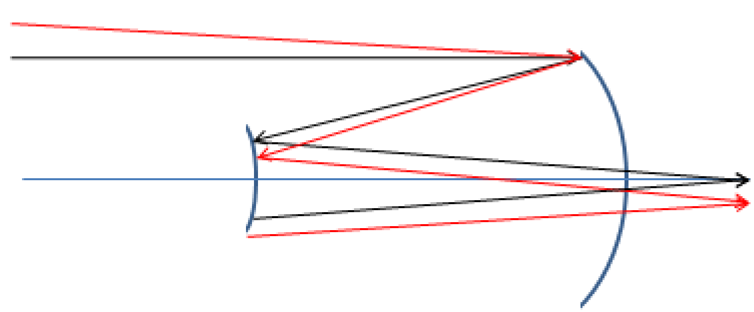
0.6 deg field of view, Photon limited			
Telescope	Accuracy	#Stars	#Stars
dia meters	uas, 1hr	Searched 1Me	Searched 1.4Me
1	0.90	96	148
1.19	0.63	132	222
1.41	0.45	222	325

As mentioned before, the photon limit is seldom reached in astrometry. Space missions such as GAIA would be photon limited for stars fainter than ~13 mag, but would be systematic error limited for brighter stars. For bright nearby stars (~7 mag or brighter) no current space telescope is within two orders of magnitude of the photon limited precision. For bright stars, the photon limit is below 1 uas in 1 hour even for modest sized (1m) telescope. There are a large number of systematic errors that prevent conventional telescope from achieving 1uas accuracy these are explained in the following sections of this paper. Broadly speaking, every element of a telescope and focal plane detector has systematic errors that can be orders of magnitude larger than 1uas. We can categorize these errors as:

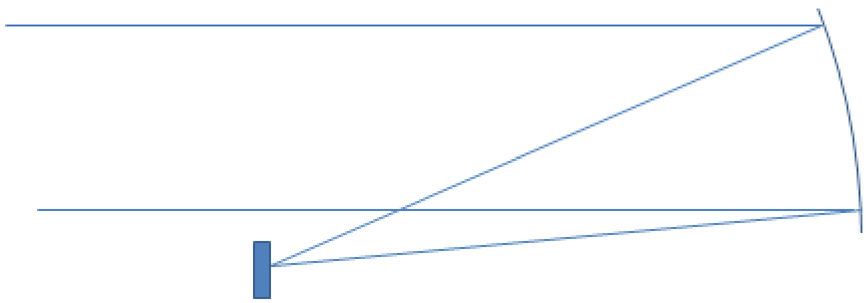
1) Optical errors
2) Focal plane geometry errors
3) PSF fitting errors (imperfect knowledge of PSF and intra-pixel QE errors)

3 Optical errors

In order to detect enough photons to reduce photon noise to below 1 uas in one hour, a modest sized telescope has to have a ~0.5 deg field of view. Normally this would mean the telescope would be TMA (three mirror anastigmatic) type of telescope. If the f/# of the primary is moderately large one might be able to use a RC (Ritchie Chretien) design. A major source of astrometric error from these telescopes comes from slight imperfections in the optics. Light from an on axis star hits the primary, then the secondary before coming to a focus on the focal plane detector. As seen in figure 1, light from an off axis star hits the same primary but has a slightly different footprint on the secondary mirror. If the secondary mirror is imperfect, the two wavefronts will be slightly different. This type of error is called beam walk error because it is caused by imperfections in an optical surface where the beam "walks" across the surface of the optic as we look at stars in different parts of the field of view.

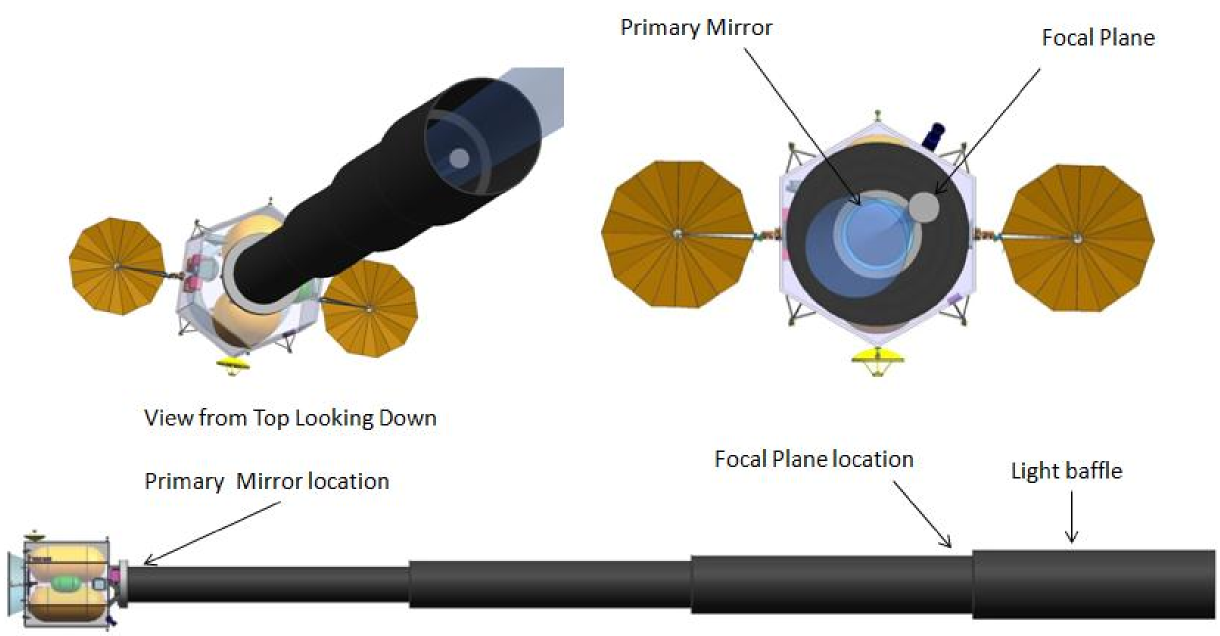


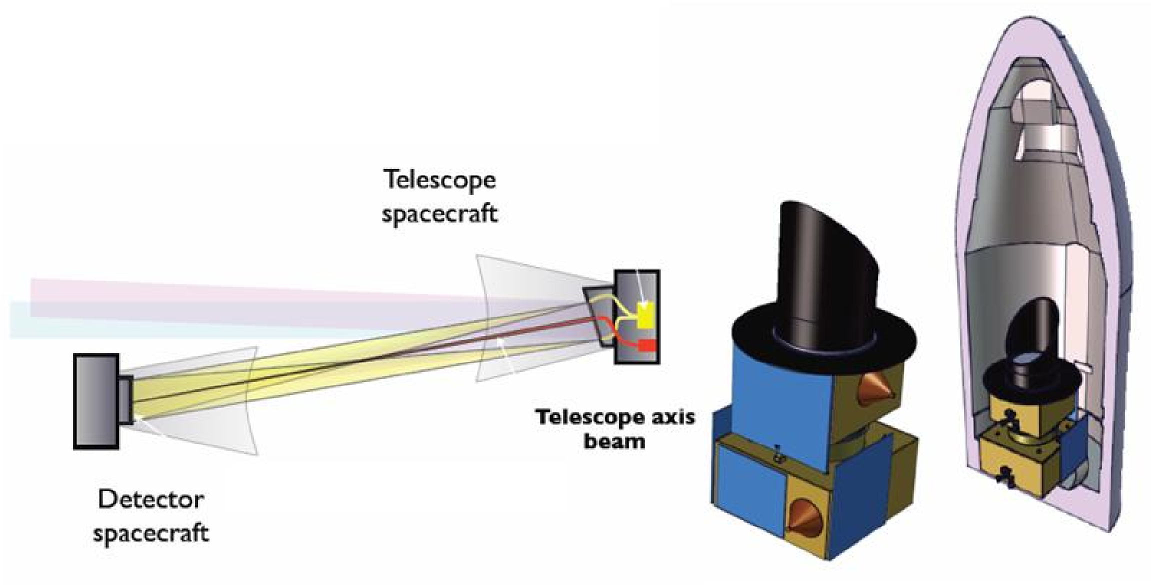
1 uas is a very small number, 5 picoradians. Stars in different parts of the field of view use different parts of the secondary mirror, if these two parts of the secondary are imperfect, which is if their average tilts are different from "perfection" by 5 picometers that would result in a 1 uas systematic error. In general it is not possible to manufacture any optic to 5 picometer accuracy. In fact it is not even possible to have an optic be stable to 5 picometers over a 5 year mission life. O. Guyon has calculated the size of this beam walk error for a TMA telescope whose secondary and tertiary mirrors are fabricated to 1nm rms surface accuracy. Over 0.5 deg field the errors can be as large as 500 uas. One approach to solving the beam walk problem is to use a diffractive element at the primary (Guyon, 2011). Another approach, the one we adopt here is to use a telescope design that has no beam walk error. If we use a telescope that has only a single surface, the wavefront errors on that one surface will be the same for every star in the field of view.



The major disadvantage of this optical design is that the f/# of the telescope has to be quite large in order to have a diffraction limited field of 0.5 deg diameter. For a 1m telescope at 0.6um, the focal length has to be ~40m. Part of the reason we chose this approach, besides the absence of beam walk errors, is that some deployed structures are being designed for space at moderate cost. NewStar a SMEX mission, an X-Ray grazing incidence telescope is using a 10m deployed boom to separate the optics with the focal plane, with a deployed boom cost that is less than $10M.

An artist concept of a deployed version of NEAT is shown below. An alternative version of NEAT using 2 separate spacecraft flying in formation, is also shown.

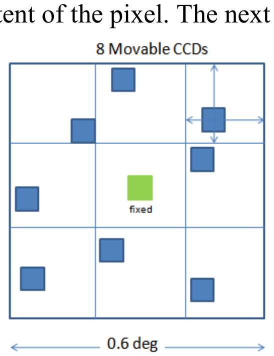




Each version of this concept has different advantages/disadvantages. The deployed version has the cost of the very long deployed telescope tube. The free flyer version has the cost of a 2nd spacecraft which needs 6 degrees of control. Its XYZ position as well as its orientation needs to precisely controlled. The cost scaling of the two concepts are also different. With a larger telescope, the separation between the optics and the focal plane gets larger. It is expected that the cost of a 1m telescope plus 40m boom may be dominated by the cost of the Boom. The cost of the free flyer version on the other hand is independent of the focal length of the telescope. Clearly at some large scale the free flyer version is more cost efficient.

4 Focal plane errors

To achieve 1 uas astrometric accuracy, not only do the optical errors have to be small, the focal plane errors must also be very small. A 1m telescope with a 40m focal length has a diffraction limited image (l/D) is 24um in diameter at the focal plane. 1 uas is ~10^{-5} of the diameter of the image. If the focal plane CCD has 10um pixels, centroiding the image to 1 uas means measuring the centroid position to 0.2 nm, or $2\text{x}10^{-5}$ pixels. There two types of focal plane errors, an ideal CCD focal plane has uniformly spaced pixels. If a 0.6 deg FOV focal plane would have ~$1.6\text{x}10^{9}$ pixels, about 40,000 pixels across the field. There are two types of focal errors. First especially in a focal plane made of a mosaic of CCDs, the pixels are not uniformly spaced to 0.2nm. In fact even with one CCD the pixel position errors are typically ~100nm. But not only are the pixel locations not accurate to 0.2nm, they are not stable to 0.2nm over a typical 5 year astrometric mission lifetime. A mosaic CCD focal plane will be built from a variety of materials, aluminum, copper, ceramic, silicon each with a slightly different coefficient of thermal expansion. The CCDs will have to be slightly cooled to reduce dark current. The CCDs are active devices that dissipate heat. 1uas over 0.6 deg field implies dimensional stability of 5 parts in 10^{10}. If we take an average CTE of 10^{-5}, this implies that the temperature and thermal gradients in the focal plane have to be stable to ~10microK over the 5 year mission life. The second type of focal plane error has to do with PSF fitting errors with pixels whose QE is not uniform over extent of the pixel. The next two sections of this paper describe these two error sources in more detail, and describe a “conceptual” solution to these problems. A companion paper in this conference (Nemati, 2011) describes the laboratory progress we’ve made towards demonstrating the conceptual solution works.

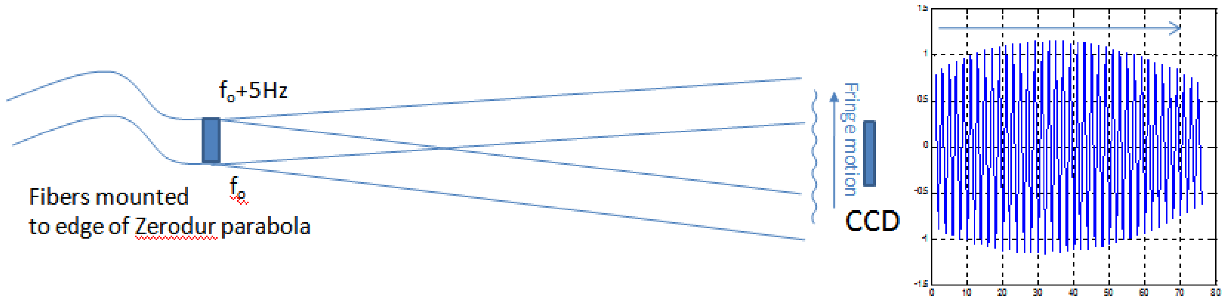


As mentioned before a fully populated focal plane with slightly better than Nyquist sampling would need a mosaic of CCDs with a total of $1.6\text{x}10^{9}$ pixels. Such a large focal plane cannot be stable to 0.1~0.2nm and it is then necessary to “measure” the location of the pixels periodically over the mission lifetime. The next section of this paper describes the metrology system we plan to use to measure the focal pixel geometry. But once we’ve paid for the metrology system, there is no reason why the focal plane has to fully populated, when we only need to measure the position of

6~10 reference stars in the 0.6 deg field. The NEAT instrument concept calls for one CCD at the center where the target star will be placed and 8 additional moveable CCDs. The total number of pixels is reduced by roughly a factor of 1000; we expect the cost of the focal plane would be reduced by roughly a factor of 10.

5 Pixel Location Metrology

To measure the position of every pixel in the focal plane, we will use a variation of heterodyne metrology used in the SIM mission.



To illustrate the concept, two optical fibers will illuminate the focal plane. The laser light in the two will be slightly frequency shifted, by a few hertz. This results a set of moving fringes on the CCD. If the frequency difference in the two fibers is 5 Hz, the fringes will move across at 5 fringes/second. If we read out the CCD at ~ 50 Hz, that provides ~10 samples per cycle, a minimum of 2 samples/cycle (Nyquist sampling) is needed to measure the fringe frequency, amplitude and phase. If we look at the output of one pixel in time, the signal should be a sine wave at 5 Hz. Another pixel's output should also be a 5 Hz sine wave. The phase difference between those two temporal sine waves is a measure of the distance (in the direction perpendicular to the fringes) between the two pixels. The use of "temporal" fringes instead of spatial fringes is why we call this heterodyne metrology. Another advantage of using temporal fringes as opposed to spatial fringe fitting arises from imperfections in the CCD. The fringe pattern that results from the interference of the light from the two fibers is very nearly perfect, both spatially and temporally. But most CCDs are geometrically imperfect at the ~100nm level, $5x10^{-3}$ pixel. Spatial imperfections in the CCD doesn't affect the quality of the temporal fringe fit. Ultimately we don't need to know the absolute location of a pixel, but we do need to know the changes in the location of a pixel at the 10^{-5} pixel level. As long as the imperfections of the CCD are constant they don't affect our measurement of the change in the pixel position. A more detailed description of CCD pixel metrology is given in the companion paper in this conference, (Nemati, 2011) as well as a separate paper (Zhai, 2011).

6 PSF Fitting

In traditional centroiding of stellar images on a CCD, one performs a least squares fit of a "model" PSF to the pixilated data. This approach can achieve centroiding to slightly better than 1/100 pixel. This traditional approach makes a number of assumptions and "guesses". To centroid an image to 10^{-5} pixels these assumptions and guesses must be replace by a much more detailed model. In an ideal telescope, the image of a star is the diffraction pattern from the telescope, the airy function. The NEAT telescope is an offaxis parabola, with no obscurations. But optical figure of the parabola is not perfect, and the focus may not be exactly correct. In addition, the offaxis images will have a significant amount of coma. Significant compared to 1 uas astrometry.

Equally important, the detector is imperfect. In traditional astrometry with CCDs, the "model" PSF is sometime a Gaussian, sometime it's the airy function (with diff spikes). The model PSF is shifted by fractions of a pixel until the pixilated model has a minimum rss difference with the data. The pixilated PSF is calculated assuming that the pixels are perfect in two ways. One it is assumed that the pixels are uniformly spaced. Two it is assumed that the QE of a pixel is 0 outside the pixel boundary and a constant value inside the pixel boundary. There are three possible sources of systematic error in traditional CCD centroiding that must be eliminated if we want to centroid to 10^{-5} pixels.

Instead of using a "model" PSF, which is a "guess" as to what the "true" image of the star is, we make use of the Nyquist theorem. The Nyquest theorem says that if we sample an arbitrary band limited function at a frequency greater than twice the bandwidth, that is sufficient to reconstruct the function perfectly (in the absence of noise). An image of a star from a telescope is a band limited function, although the function is in space not in time. There are no spatial frequencies above 1 cycle per λ/D. In performing the least squares fit, we have to "move" the pixilated model PSF by fractions of a pixel. Moving the "true" psf by fractions of a pixel can be done with Fourier interpolation.

There are two CCD/focal plane related errors, one the non-uniform spacing of the pixels was mentioned earlier, and two the non-uniform intra-pixel QE must also be calibrated. There are two complementary ways to measure the QE(x,y) within every pixel. One is to image a small spot of light, a spot whose diameter is much smaller than a pixel, on the CCD and move the spot around. This measures QE(x,y) directly. Our approach is to measure the Fourier transform of QE(x,y), by putting a series of sinusoidal patterns of different spatial frequency and orientation across the detector. The later technique is a modest extension of the metrology scheme we use to measure the position of every pixel. If we used a small spot to calibrate QE(x,y) we'd have to be very careful in locating that spot not just on one pixel but across 10's of thousands of pixels.

The companion paper at this SPIE conference (Nemati, 2011) describes the approach and our initial results in more detail, the signal processing is described in more detail in another publication (Zhai, 2011).

7 Summary

In summary, the NEAT concept is a new approach to achieving microarcsec astrometric accuracy with a modest sized telescope. An alternative approach for microarcsec astrometry using a diffraction spikes generated by a mask at the pupil of a TMA telescope (Guyon, 2011) has the same goal, but use a totally different approach. The NEAT concept has a potential fundamental (photon noise) advantage, in that it makes full use of the bright reference stars. The diffraction spikes are rather faint and reference stars brighter than ~17 mag are limited by photon noise of the spikes rather than photon noise of the reference stars. NEAT only uses the reference stars between 10 and 12 mag. The other difference in the two approaches is how CCD focal plane errors are handled. The PECO astrometry approach rotates the telescope ~90 deg around the line of sight, to move the reference stars across many pixels to average out the pixel errors. Since pixilation errors are $\sim 10^{-2}$ pixels this approach assumes that sqrt(N) can provide a 1000 fold increase in accuracy. The NEAT approach uses precise calibration of the focal plane, and only relies on sqrt(N) averaging for the last factor of 3~5.

The ability to do uas astrometry with a modest sized telescope, potentially reduces the cost of an astrometric mission to find Earth-Clones around nearby stars by a significant factor. In the current budget climate, it may be the only approach to finding 1 Earth mass planets around nearby stars for the next several decades.

ACKNOWLEDGEMENTS

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