A concept for High Precision Astrometry with a Space Coronagraph

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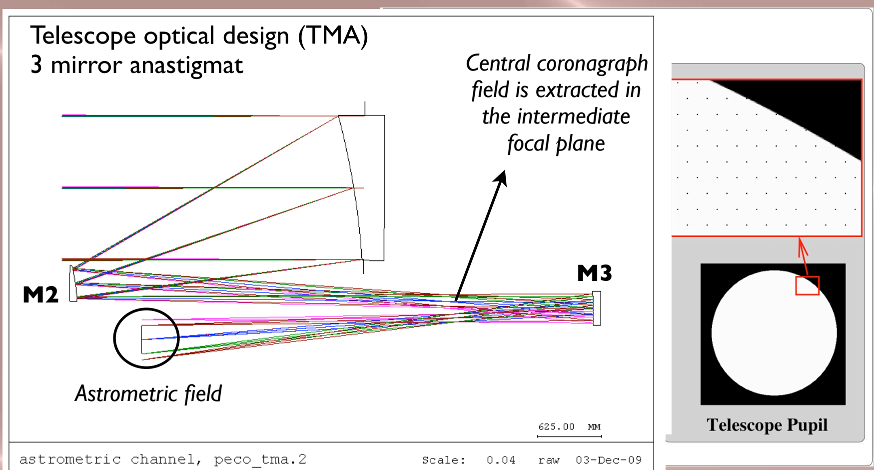
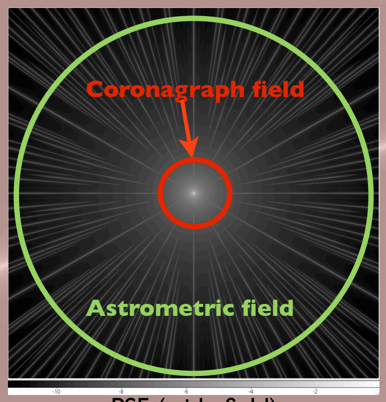
High precision (micro-arcsecond) astrometry of nearby bright stars is theoretically (in the photon noise limit) possible with a space coronagraph with the addition of a wide field diffraction limited camera imaging an annulus of background stars around the central coronagraphic field. With micro arcsecond accuracy on a 1.4-m telescope, the mass of all planets that can be imaged by the coronagraph would be estimated. Simultaneous imaging and astrometric measurements would reduce the number of astrometric measurements necessary for mass determination, and reduce confusion between multiple planets and possible exozodiacal clouds in the coronagraphic image. While scientifically attractive, this measurement is technically very challenging, and must overcome astrometric error terms, which, in conventional telescopes, are several orders of magnitude above the photon noise limit. This paper investigates how some of these limitations could be overcome with new technical approaches, and identifies outstanding issues. The astrometric measurement is performed by simultaneously imaging background stars and diffraction spikes from the much brighter coronagraphic target on the same focal plane array. The diffraction spikes are generated by a series of small dark spots directly on the primary mirror to reduce sensitivity to optical and mechanical distortions.

Principle & optical design



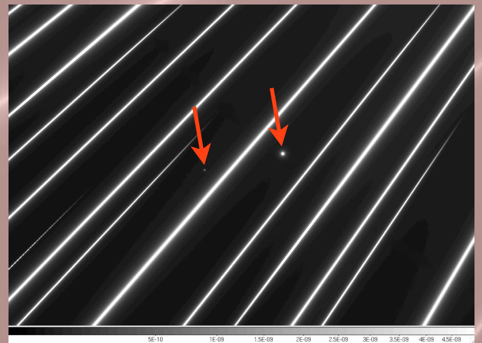
The telescope delivers a narrow field to the coronagraph and a wide field to the astrometric camera. A grid of small black dots on the primary mirror produces diffraction spikes which are superimposed on the wide field image of numerous background stars.



PSF (wide field)

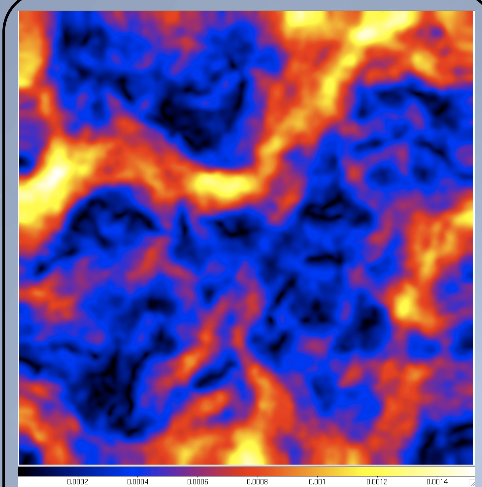
Simulated PSF (log scale, coronagraph pickoff mirror removed to show simultaneously the central and outer parts of the PSF). This polychromatic (FWHM from 0.49 to 0.91 micron) simulated PSF shows the radially-elongated diffraction speckles created by the series of dark dots on the primary mirror. The length of each spike is proportional to both its distance from the optical axis and the wavelength range. This image is 3.8 arcmin x 3.8 arcmin, with 28 mas pixels (8192x8192 pixel). The total flux in the spikes is 0.42% of the flux in the central part of the PSF. In the observing configuration with a coronagraph pickoff mirror, the central part of the PSF (a few arcsec in radius) would be blocked from the wide field camera.

The position of the central star is measured against the background field of fainter stars using the diffraction spikes. The diffraction spikes are referenced to the central star, and also encode astrometric distortions in the optical system.



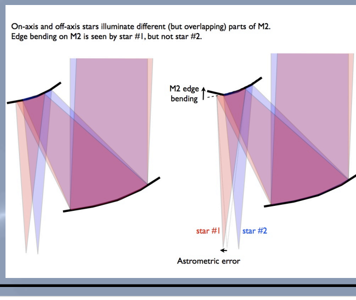
Off-axis PSF region (sqrt scale). The diffraction spikes elongated due to plate scale chromaticity. The surface brightness of the spikes is approximately 1e-7 of the central peak (for a mV=5 target, these spikes have the same surface brightness as a mV=22.5 star). Two faint stars have been added at contrasts 1e-7 and 1e-9 (mV=22.5 and mV=27.5 for a mV=5 central star brightness).

Calibration of astrometric distortions



Astrometric distortion amplitude (linear scale from 0 to 1.5mas) induced by realistic surface errors in M2 and M3 for the TMA design shown in this poster. A PSD provided by L3/Tinsley obtained on similar size optics was used to generate surface errors. The map covers a 0.46 deg x 0.46 deg field, and was obtained by 3D raytracing using 2e11 rays.

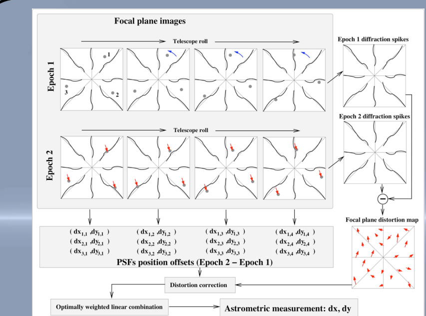
Imaging astrometry is hampered by astrometric distortions introduced by the optics (and the atmosphere for ground based astrometry). Any wavefront error introduced ahead or after the telescope's pupil plane creates variations in the plate scale in the focal plane. This effect is known as tilt anisoplanatism, and is the main limitation to precision ground based astrometry (Cameron et al. 2009). In space, with no atmosphere, astrometric distortions are much smaller, but still exist due to bending in optics within the telescope and instrument. The figure on the right shows how changes in the telescope's secondary mirror shape produce an astrometric error.



The scheme proposed here directly addresses this problem by adding to the focal plane a reference pattern (diffraction spikes) which is introduced directly on the aperture stop (primary mirror PM) of the telescope. The dots on the PM act as a diffraction grating creating secondary beams which emerge from the primary mirror with slightly different angles and travel through the optical system up to the focal plane. **Light from an off-axis star and light from a nearby diffraction spike go through the same path in the optical system** (telescope + instrument), therefore eliminating the anisoplanatism problem in a differential measurement between spikes position and background star position.

The proposed scheme is also insensitive to large scale focal plane array distortions, as they will affect equally the background stars and the diffraction spikes. Wavefront errors on the primary mirror do not produce an astrometric error as they are common to both the diffracted beams and the beam from the astrometric reference stars.

Telescope roll is used to average down residual astrometric errors (flat field errors, unknown PSF shape, small scale astrometric distortions).



A distortion map is built from the motion of the spikes on the detector between 2 epochs. This provides a good correction of low order distortions. The telescope is rolled during the observation to average astrometric distortions on small spatial scales (detector pixel size variations, high order distortions on optics).

Expected performance & outstanding issues, ongoing work

The astrometric performance could potentially be below 1μas if the telescope is sufficiently stable in time and the astrometric errors in the telescope+detector system are well calibrated by the spikes. A few key terms in the error budget are shown in the table on the right. In the photon noise limit, even with a modest 0.1sq deg field, the combined flux from all stars between m_V = 10 and m_V = 27 is sufficient for sub-μas astrometric measurement in a few hours (at galactic pole).

Ultimately, the actual precision will be driven by wavefront and detector stability over long periods of time, and based on controlling a slew of instrumental errors which would be difficult to calibrate if variable in time. We are currently developing detailed simulations which take into account the thermally driven variations in the system.

This concept is a good match to a coronagraph system, both scientifically (improved detection and characterization thanks to simultaneous astrometry + coronagraph images) and technically (need for a stable optical telescope assembly).

astrometric error terms (1 day observation, 1.4m telescope, 0.1 sq deg field, PM spots covering 4% of surface)

Error term	Value (μas)	notes, tradeoffs
Photon noise on background stars	0.13 μas	Assumes Nyquist sampling. Combined signal from stars with 10<m_V<27
Photon noise (starlight + zodi) on diffraction spikes measurement	poorly known, function of system stability	Driven by stability of optical system. Converges to zero in highly stable system (spikes can be co-added over long period of time). Can be reduced by designing the PM mask for brighter spikes or fewer spikes.
Distortions due to unknown static error in optical surfaces	<0.1μas	for 1" per year proper motion star and 1.5nm surface quality M2 and M3
Uncalibrated detector distortions	To be computed focal plane stability is an issue	Mitigated by telescope roll. If too large, could be calibrated prior to launch and on orbit (observation of dense star field)
Time-variable distortions due to change in optics and alignment	To be computed, function of system stability	Slow changing low spatial frequency distortions are most effectively calibrated with the spikes. Faster, high spatial frequency distortions poorly calibrated but will average down better with telescope roll

For more details on this concept and simulations: http://www.naoj.org/staff/guyon/04research.web/astrometry.web/astrometry.html

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