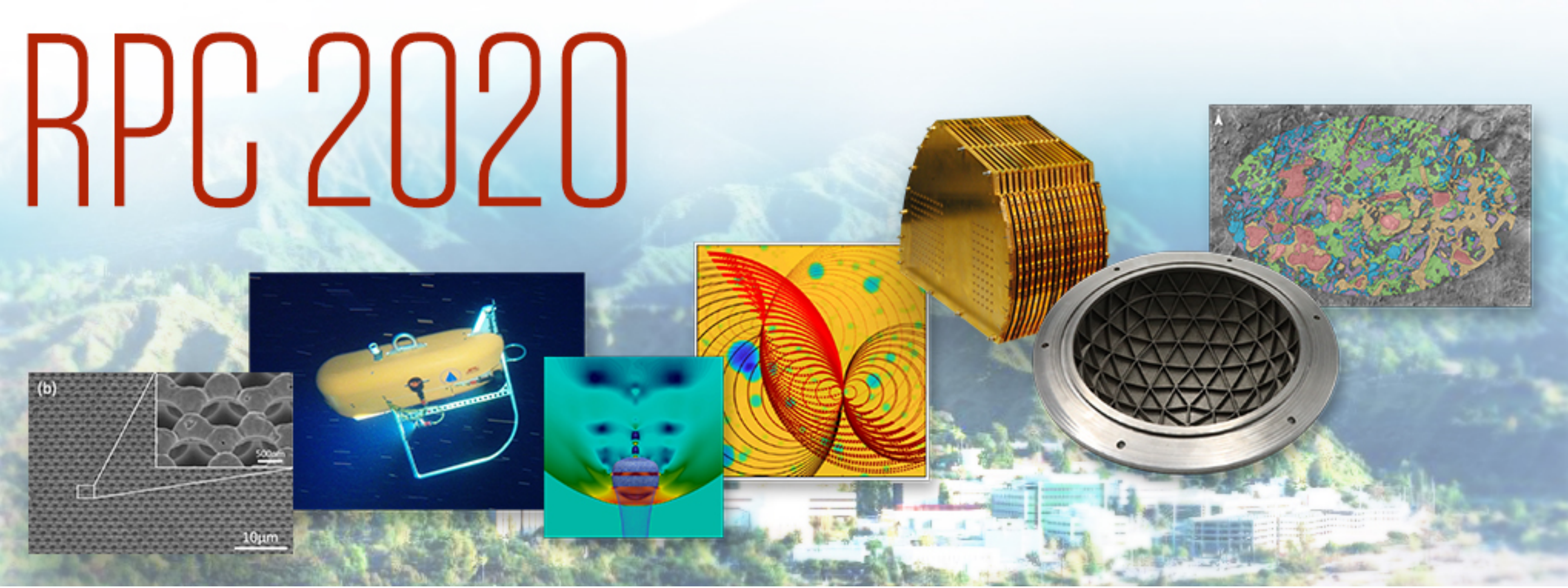

Virtual Research Presentation Conference

Visible Light Adaptive Optics for EPRV for Exoplanet Science

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Program: Spontaneous Concept

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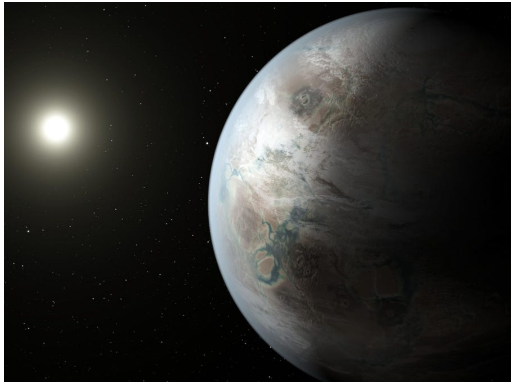
Tutorial Introduction

- The radial velocity (RV) technique measures the Doppler shift of star light as the host star gets tugged by an orbiting exoplanet. With enough precision, it is possible to detect Earth-like planets orbiting solar type stars (i.e. potentially life bearing.)
- NASA and the NSF are planning a measurement campaign to detect Earth-like planets around Sun-like stars. These would serve as targets for HabEx or LUVOIR.
- The conventional approach is to do this with large spectrographs that have their image blurred by the atmosphere. Alternatively, an adaptive optics system can correct for atmospheric turbulence and shrink the blurred image to the diffraction limit and couple the light into a single mode fiber
- This reduces the size of spectrograph, making it more thermally and mechanically stable. The reduce size also saves money, reduces development time and most importantly, reduces RV measurement errors.
- In addition, adaptive optics eliminates some sources of error, further increasing the measurement precesion
- The challenge is that these measurements are best done at visible wavelengths because of the stellar properties. Visible light AO is harder because of the shorter wavelengths.



Methodology

a) We studied the error budget for EPRV measurements and considered which error terms will be eliminated by an AO system. We also thought about any new sources of error that an AO system might introduce.

b) We carried out a parametric study of the different factors in an AO system and studied how they will impact the system design

c) We recommended several hardware elements that need to be considered. These recommendations are based upon looking at past visible AO systems and the results of the other elements of our study

Results: EPRV Error Budget Analysis

Areas of likely improved performance:

Fiber and illumination errors:. The litany of RV errors associated with guiding errors, pupil variations, imperfect fiber scrambling and mode mixing are effectively eliminated by the stable PSF that an AO system creates.

Scattered sunlight contamination: An AO-fed system will only sample a tiny amount of the sky and almost eliminate scattered sunlight contamination.

Together, these error sources account for a **47% reduction of the estimated errors** on the current state-of-the-art seeing-limited instruments. The AO fed instrument can also be made much more compact and this will lead to increased stability, yielding decreased errors.

Areas that need to be studied further:

Atmospheric Dispersion Correction: AO fed systems are more sensitive to imperfect atmospheric dispersion correction. ADC correction. Any imperfect correction of the chromaticity at the telescope focal plane will lead to variations in the effective fiber coupling efficiency as a function of wavelength, which will introduce systematic reweighting of the stellar spectral energy distribution (SED).

Sensitivity to seeing variations: The PSF will vary as seeing varies. This results in a modulation of the recorded stellar SED across the bandpass, and may require novel data reduction techniques to mitigate.

Resea

KPF PRV ERROR BUDGET SPREADSHEET, ADAPTED FOR AO-BASED SYSTEM

All units in cm s^{-1}

Instrumental errors (uncalibratable):	14.39
Fiber & illumination	7.35
Calibration source modal noise	0.00
Continuum modal noise	0.00
Near-field scrambling	0.00
Far-field scrambling	0.00
Stray light & ghosts	5.00
Fiber-fiber contamination	5.00
Polarization	2.00
Focal ratio degradation (science)	0.00
Focal radio degradation (calibration)	0.00
Double scrambler drift	0.00
Detector effects	7.07
Pixel center offsets	5.00
Charge transfer inefficiency	5.00
Barycentric correction	1.73
Algorithms	1.00
Exposure midpoint time	1.00
Coordinates and proper motion	1.00
Reduction pipeline	10.00
Software algorithms	10.00

Instrumental errors (calibratable):	18.53
Fraction of errors calibrated:	0.9
Calibratable error contribution:	1.85
Thermo-mechanical	12.13
Thermal stability (grating)	3.00
Thermal stability (cross-disp.)	5.00
Thermal stability (bench)	4.00
Thermal stability (cameras)	6.80
Vibrational stability	1.00
Pressure stability	5.00
Zerodur phase change (Echelle)	5.00
Detector effects	14.00
Pixel inhomogeneities	5.00
CCD thermal expansion	5.00
Readout thermal change	11.00
Charge transfer inefficiency	5.00

Ignored in SMF-based, AO-fed systems
Likely improved in SMF-based, AO-fed system
Potentially worse in AO-based system

Calibration source (uncalibratable):	15.00
Calibration accuracy	11.18
Wavelength stability	10.00
Photon noise	5.00
Calibration process	10.00
Software algorithms	10.00

External errors (uncalibratable)	11.56
Telescope	5.80
Guiding (")	0.00
ADC	5.80
Focus	0.00
Injection angle variations	0.00
Atmospheric effects	10.00
Micro-telluric contamination	10.00
Scattered sunlight contamination	0.00

Total instrumental error (cm s^{-1}):	23.9
% improvement over seeing-limited	52.3

The Keck Planet Finder error budget if it was AO fed. Error terms highlighted in blue are effectively zeroed out when combining AO and single-mode-fiber illumination. These errors make up ~50% of the overall error budget for seeing-limited systems. Terms highlighted in green are those that are likely to improve when moving to smaller, diffraction-limited spectrograph designs enabled by the AO illumination. Sources highlighted in red are areas where the AO-based architecture may lead to worse performance and require further study.

Parametric Studies

- Studied the impact of a number of AO parameters on Strehl ratio, which is proportional to fiber coupling efficiency. Here are a few key takeaways:
- Chromatic errors make it difficult to get useful results at u-band. Realistically, we can’t operate below 400nm.
- We can make a 10m telescope produce high Strehl ratios at g-band, but it requires a 4000 actuator deformable mirror which is experimental. This will be expensive. A 3m telescope with a standard commodity mirror performs even better at a lower development risk. (Though, the 10m has a higher instrument SNR because of its larger collecting area.)
- Instrumental errors such as non-common path errors, calibration errors, high frequency optical surface errors must be addressed and reduced, otherwise these will dominate the atmospheric error terms.

Instrument Recommendations

- Use a Pyramid WFS – Our simulations showed a 10-15% increase in the light coupled into the spectrograph with the use of a pyramid WFs over a conventional Shack-Hartmann WFS
- Stabilize the Pupil – The pupil can move around on the WFS and fiber feed due to flexure in the AO system and telescope, and due to ADC activity. This needs to be stabilized with active control.
- Minimize high frequency telescope surface errors – These will not be corrected by the AO system.
- Improve fiber coupling – Use PIAA lenses to reshape the beam into the optimal shape for a single mode fiber. This will increase the throughput of the system by 30%.
- Atmospheric Dispersion Correction – A high quality ADC is needed, common t[illegible]he entire AO system and coupled with active pupil stabilization.

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