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The Fourier-Kelvin Stellar Interferometer: an achievable, space-borne interferometer for the direct detection and study of extrasolar giant planets

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Abstract. The Fourier-Kelvin Stellar Interferometer (FKSI) is a mission concept for a spacecraft-borne imaging and nulling interferometer for the near to mid-infrared spectral region. FKSI is a scientific and technological pathfinder to the Darwin and Terrestrial Planet Finder (TPF) missions and will be a high angular resolution system complementary to the James Webb Space Telescope (JWST). There are four key scientific issues the FKSI mission is designed to address. These are: 1.) characterization of the atmospheres of the known extra-solar giant planets, 2.) assay of the morphology of debris disks to look for resonant structures characteristic of the presence of extrasolar planets, 3.) study of circumstellar material around a variety of stellar types to better understand their evolutionary state, and in the case of young stellar systems, their planet forming potential, and 4.) measurement of detailed structures inside active galactic nuclei. We report results of simulation studies of the imaging capabilities of the FKSI, current progress on our nulling testbed, results from control system and residual jitter analysis, and selection of hollow waveguide fibers for wavefront cleanup.

Keywords. instrumentation: high angular resolution, techniques: interferometric, space vehicles: instruments, planets and satellites: general, planetary systems: formation, Galaxy: nucleus.

1. Introduction

The high spatial and spectroscopic resolving capability of the FKSI instrument together with its calculated sensitivity will position it as an important facility for the study of a range of astronomical phenomena. Its science objectives are, very broadly, to directly detect extrasolar giant planets (EGP), study debris disks and the evolution of protostellar

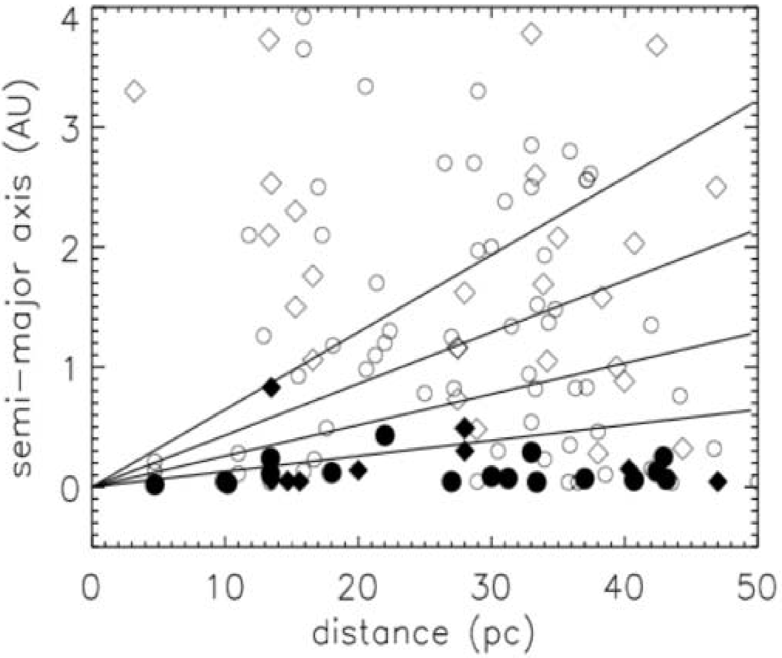

Figure 1. Distance (in parsecs) and orbital radius (semi-major axes, in AU) for 140 of the known extrasolar planets. The planets within at least a 40 degree field of regard, and nominally detectable by FKSI, are plotted with filled symbols. Circles indicate planets within a 20 degree field of regard, and diamonds indicate additional detectable planets if the field of regard is extended to 40 degrees. The lines correspond to the first fringe maximum for nulling interferometers of baselines 8, 12, 20, and 40 m (top to bottom).

and evolved stellar systems, and to facilitate the study of extra-galactic star formation regions and the extended neighborhoods of active galactic nuclei.

The detection and study of EGPs will be greatly facilitated by a dedicated nulling interferometer on a satellite platform operating at infrared wavelengths. To answer key questions about these planets FKSI will be able, depending on configuration, to detect at least 25 known EGPs and make precise determination of their orbital parameters. (See figure 1.) The spatial resolution of the Fourier-Kelvin Stellar Interferometer together with the instrument's $R = 25$ spectroscopic capability will allow the direct detection and analysis of photons from EGP under certain conditions of orbital phase and angular separation. (See Danchi, *et al.* 2003b.) These measurements will enable studies of the environmental conditions to which the planet is subject. They will also provide a means of measuring the composition of the planet's atmosphere.

FKSI exploits the orbital dynamics of close-in planets. Using a spatial dither of the null fringe, FKSI will be able to reconstruct the astrometric orbit of the planet and, in combination with radial velocity studies, derive the mass. In addition to mass, FKSI observes the variation in the planet's infrared spectrum as a function of phase, and facilitates characterization of the planet's thermal state and composition. In favorable cases, data obtained using FKSI could even allow scientists to make inferences about dynamical properties such as winds. This approach of exploiting the infrared brightness of close-in planets builds on the transit and radial velocity studies, which have detected most of the known extrasolar planets.

While direct detection of EGPs is a principal goal of the FKSI mission, study of stellar environments in general will also be greatly facilitated by the instrument's spatial and spectral resolving power. With FKSI, scientists may observe the formative stages of planetary systems, protoplanetary disk structure, the evolution of primordial exozodiacal dust, and debris disks about various stellar types. These observations may then be used to determine the characteristics of circumstellar material that could lead to planet formation or the evolution of the habitable zone about post-main sequence stars. These studies would facilitate refinement of the target lists and science goals of the TPF mission.

2. Design and Mission Concept Approach

Our team, lead by our Principal Investigator, Dr. W. C. Danchi, consists of scientists from a broad array of institutions and, together with engineering support from GSFC, has expended significant effort to develop a range of design options for FKSI. We have studied various beam combination techniques and array architectures in preparation for submission of FKSI as a Discovery-class mission. These design studies were conducted initially at GSFC's Instrument Synthesis and Analysis Laboratory and the Integrated Mission Design Center. These are important functions within GSFC's infrastructure used to facilitate rapid vetting of various mission and instrument design concepts. These studies were then augmented by the work of a larger, focused team of experienced scientists and engineers dedicated to the FKSI mission. The resulting design is a nulling interferometer configuration with an optical system consisting of two 0.5 m telescopes on a 12.5 m boom feeding a symmetric Mach-Zehnder beam combiner. A null tracker and hollow-core fiber for wavefront cleanup further augment the system and allow it to produce the required .01% null of the central starlight. A thorough description of the design study and technology trade process was published recently. (See Danchi, *et al.*, 2003a.)

3. Dynamic Jitter Analysis and the Nulling Budget

An in-depth control system and dynamic jitter analysis has been conducted for the FKSI mission. (See Hyde, *et al.*, 2004) This analysis consisted of several distinct phases. First, a structural finite element analysis was conducted using a NASTRAN model of the spacecraft bus and instrument payload systems. A normal modes analysis was performed and mode shapes and frequencies provided for the integrated model. Important nodes in the model were input degrees of freedom (DOF) at the reaction wheel assemblies (RWA) mounted to spacecraft, output DOFs at each optical element in train, and interface DOFs at the four mounting points of spacecraft to payload. The first six modes of the combined payload/spacecraft are the isolator modes and range from 0.3 to 3 Hz in the nominal design. Higher modes include boom-flapping modes at 5.6 and 7.3 Hz. A mode at 25.5 Hz includes the motion of the combiner relative to the siderostats and strongly influences optical path delay.

The second phase of the analysis consisted of development of an optical model and included tracing of ray bundles from the entrance pupils above the siderostats through the optical train to the angle tracker, fringe tracker, and nuller detectors. This model may be described as a first-order Taylor expansion of the optical path lengths of a grid of rays traced through the system, uniformly spaced at the entrance pupil. The variables expanded upon are the rigid body DOFs for each optical component in the system. All ray tracing for the linear optical model was performed ahead of time to generate linear sensitivities that acted as transfer functions converting rigid body motions of optical components to absolute image motion at the detectors and wavefront error induced due to the misaligned components. Comparing wavefront maps generated from the sensitivities to those generated by ray tracing show less than 1 percent difference for random perturbations of one micron motions or one micro-radian tilts.

The third modeling effort included the normal spacecraft attitude control as well as control of many optical elements in the payload. This model, carried out in MATLAB Simulink, includes the spacecraft attitude control system (ACS) as well as the two types of continuous control loops in the payload, the optical path delay (OPD) and the angle steering mirrors (ASM). The ACS uses star trackers and gyros to estimate the pointing of the spacecraft bus and controls this to about 1 arcsec RMS in roll and pitch. The instrument errors consist of two tilt errors and the OPD. These are sensed by the angle tracker and fringe tracker respectively and are controlled in a feedback loop to the angle steering mirrors and the optical delay line (ODL) fine stage. Sensor noise in the FT accounts for about 5 nm of OPD error. Actuation noise in the ODL fine stage accounts for about 5 nm of OPD error. The low frequency ACS control residual of about 1 arcsec results in about 60 μm of OPD which is reduced to less than 7 nm by pathlength variation control. By including an unloading loop from the ODL command back to the pitch axis of the ACS, the ACS control residuals are further reduced by a factor of 100. This means that the fine stage of the ODL needs only 2 μm of stroke.

A forth element is the passive vibration isolation between the payload and the spacecraft bus. The isolator system reacts to the relative displacement between the payload and spacecraft and generates relative forces that act on the two masses. The transfer function between relative forces and relative displacements between the two masses behaves similarly to a high-pass filter. In the model of this system, the isolator physical parameters are mapped directly from three isolator design parameters that describe the desired isolation behavior. The baseline design has an isolation corner frequency of approximately 0.8 Hz with approximately 40 percent damping.

Finally, the results of the discipline models outlined above were integrated into a single system model. The model integration and subsequent analysis was performed in the Disturbance-Optics-Controls-Structures (DOCS) environment, a suite of tools developed at the Massachusetts Institute of Technology for performing integrated modeling, critical parameter identification, and system design. The influence of each design parameter and anticipated disturbance was explicitly evaluated. Critical parameters were then traded to generate a design that meets requirements optimally with respect to mission cost and risk.

Null depth, a critical final output parameter of the integrated analysis, is affected by alignment, control, and dynamic stability concerns. Science drivers require a 0.01 percent null depth that may then be allocated across the derived null depth loss contributors. Null loss formulae subsequently yield a tolerance on parameter for each subsystem. The high-fidelity analysis allows the budgeted OPD tolerance term to be further broken down into separate component contributions, which are incoherent and are, therefore, root-sum-squared (RSS) rather than directly summed. Finally, these parameters are directly applied to FKSI testbed OPD components as design requirements. The ACS, RWA, and boom noise contributions are RSSed and are equated in the testbed environment to residual seismic and air turbulence perturbations.

4. The Nulling Stellar Interferometry Testbed

The FKSI testbed is now fully funded and is being built in the Horizontal Flow Facility at NASA's Goddard Space Flight Center in Greenbelt, Maryland. This testbed will allow the instrument designers to evaluate technically challenging aspects of the design. In particular, the instrument's symmetric Mach-Zehnder nulling architecture will be examined together with a novel ditherless quadrature phase detector approach. Significant progress has already been made on the testbed, which has now transitioned from visible to monochromatic IR testing.

The nulling architecture of the testbed consists of a symmetric Mach-Zehnder beam combiner. A laser beam is collimated by an off-axis parabola, which is then passed through a mask with two apertures. This mask simulates the beams coming from the siderostats of the proposed two-aperture version of the FKSI design. These beams then enter a pair of mirror-symmetric right angle periscopes, and are rotated 180 degrees resulting in a field reversal, which affects the incident polarization states by reversing the s and p plane reflections. The beams are then relayed through cats-eye retro-reflectors in order to control the interference of the beams in delay space without effecting polarization. After the beams are passed through the delay line, two beamsplitters split both beams, and two more beamsplitters re-combine them. The beamsplitters and the fast steering mirrors are controlled by picomotors for fine adjusting. All four recombined beams are sent to four detector channels, which are used to gather both scientific data and metrology.

After determining the cause and solution to several alignment limitations using a 632 nm source, we have now converted to a 1.15/3.39 μm source and have upgraded several optics. In particular, we have replaced all silver fold mirrors with uncoated gold and replaced commercial off-the-shelf (COTS) visible light beamsplitters with (50/50) IR beamsplitters. Some near-term goals include the integration of hollow, single-mode fibers for wavefront cleanup and the addition of a phase tracking control system. Phase tracking will be performed with a novel ditherless quadrature phase detector and a voice coil or piezo actuator driven in closed loop using a digital signal processing system. The phase tracking control loop will have a high bandwidth to achieve good disturbance rejection capability even at high frequency where the structural resonant modes dominate. Picomotor actuators set on four mirrors, four beamsplitters and the cats-eye phase-delays will be controlled with control system software in order to continuously track and steady the fringe during measurements. Fringe contrast will be further improved by mounting hollow fibers in the detector space to clean the wavefront of aberrations.

The hollow glass waveguide (HGW) fibers chosen for the testbed have been fabricated at Rutgers University and will soon be integrated into the FKSI testbed. These HGWs were fabricated using wet-chemistry methods to first deposit a silver layer on the inside of silica glass tubing and then to form a silver halide dielectric layer over the metallic film. (See Harrington, 2004.) One advantage of these HGW fibers over the more typical solid-core polycrystalline (PC) fibers is that they can be created with a very flat spectral response in the 3 - 20 μm spectral region. In contrast, PC fibers often suffer from mode mixing and higher loss than HGW fibers due to the extrusion pressure necessary to force the preform through the die. This results in the non-circularity of the core and cladding and contributes to transmission of multiple modes. HGW, in contrast, have no Fresnel loss and require no end polishing to attain single mode performance. HGW made using silica tubing such as those chosen for the FKSI testbed are very robust, and, most importantly, have been shown to have more than 20dB of mode rejection between the HE11 and HE12 modes even though their bore size is significantly greater than the wavelength of light. The FKSI testbed team will be testing various lengths of 100, 150, and 180 μm HGW in the near future and will report our findings.

5. The Observatory Simulation Code

The FKSI observatory simulation code, written in IDL, is used to evaluate the detectability of known radial velocity planets. The code models the instantaneous properties of the null fringe with realistic path difference errors, and convolves the disk profile of a limb-darkened star and orbiting planet with the fringe transmission. Repeating this convolution as the interferometer rotates for a specified number of rotations at a specified rate, the code generates synthetic signals, accounting for detector noise, stellar photon noise, and noise from thermal background within the instrument and from zodiacal emission in our solar system. The code can also generate synthetic signals from hypothetical zodiacal dust in the extrasolar system using ZODIPIC, a software tool developed by Marc Kuchner to compute images of exozodiacal clouds. User input to the simulation code can specify the bond albedo of the planet, and a parametric representation of how stellar irradiation is redistributed on the planetary disk. Phase-dependent variations in the planetary spectrum are also included, with orbital parameters from the Doppler data, or specified by the user. This simulation code was used to evaluate the detectability by FKSI of all know extrasolar planets as of July, 2005.

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