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THE FOURIER-KELVIN STELLAR INTERFEROMETER: A practical interferometer for the detection and characterization of extrasolar giant planets

W. C. Danchi^a, R. J. Allen^b, D.J. Benford^a, D. Deming^a, D. Y. Gezari^a, M. Kuchner^c,
D. T. Leisawitz^a, R. Linfield^d, R. Millan-Gabet^e, J. D. Monnier^f, L. G. Mundy^g, C. Noecker^d,
J. Rajagopal^{a,g}, L. J. Richardson^a, S. Rinehart^a, S. Seager^h, W. A. Traub^c, D. Wallace^a

^aNASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

^bSpace Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA

^cHarvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

^dBall Aerospace, Boulder, 1600 Commerce St., CO 80301, USA

^eCalifornia Institute of Technology, 1201 E. California Blvd., Pasadena, CA 91125, USA

^fUniversity of Michigan, Astronomy Department, Ann Arbor, MI 48109, USA

^gUniversity of Maryland, Astronomy Department, College Park, MD 20742, USA

^hCarnegie Institution of Washington, 5241 Broad Branch Rd., NW, Washington, DC 20015, USA

ABSTRACT

The Fourier-Kelvin Stellar Interferometer (FKSI) is a mission concept for a nulling interferometer for the near-to-mid-infrared spectral region (3–8 μm). FKSI is conceived as a scientific and technological precursor to TPF. The scientific emphasis of the mission is on the evolution of protostellar systems, from just after the collapse of the precursor molecular cloud core, through the formation of the disk surrounding the protostar, the formation of planets in the disk, and eventual dispersal of the disk material. FKSI will answer key questions about extrasolar planets:

- What are the characteristics of the known extrasolar giant planets?
- What are the characteristics of the extrasolar zodiacal clouds around nearby stars?
- Are there giant planets around classes of stars other than those already studied?

We present preliminary results of a detailed design study of the FKSI. Using a nulling interferometer configuration, the optical system consists of two 0.5m telescopes on a 12.5m boom feeding a Mach-Zender beam combiner with a fiber wavefront error reducer to produce a 0.01% null of the central starlight. With this system, planets around nearby stars can be detected and characterized using a combination of spectral and spatial resolution.

Keywords: mid-infrared, nulling interferometer, extrasolar planets, giant planets, space interferometer

1. INTRODUCTION

At the present time, more than 100 extra-solar planets have been found using high-precision Doppler velocity searches [1]. Considerable information exists about the masses of the planets (but with the $\sin i$ ambiguity), the orbital periods and eccentricities. In a few cases planetary systems have been found [1]. Recently, sodium absorption in the atmospheric spectrum of the transiting planet has been measured. [2]. However, little else is known about these planets. Basic questions of great scientific importance include the density of the planets, i.e., whether they are rocky or gas giants (although most are expected to be gas giants), and the constituents and physical conditions of their atmospheres. Some further progress can be expected from ground-based astronomy, namely, nulling [3], and differential phase [4] experiments with the Keck Interferometer [5].

However, a dedicated interferometer located on a satellite platform provides the greatest long-term potential for progress on extra-solar planet research at infrared wavelengths, which eventually will lead to the ambitious and technically difficult Terrestrial Planet Finder (TPF) [6] and Darwin missions [7] for the detection and characterization of earth-like planets around the habitable zone [8].

Our team has been studying various interferometer architectures and beam combination techniques, and evaluating the relevant science and technology tradeoffs in preparation for future proposal opportunities for the FKSI mission. Some of the technical challenges include the development of the cryocooler systems necessary for the telescopes and focal plane array, light and stiff but well-damped truss systems to support the telescopes, and lightweight and coolable optical telescopes.

We present major findings of detailed design studies of the FKSI beginning with a design consisting of five one meter diameter telescopes arranged along a truss structure in a linear non-redundant array, cooled to 35 K. A maximum baseline of 20 m gives a nominal resolution of 26 milli-arcseconds (mas) at 5 μm . Using a Fizeau (image-plane) beam combination technique, a relatively simple focal plane camera could be used to obtain both Fourier and spectral data simultaneously for a given orientation of the array. The spacecraft is rotated about the line of sight to give sufficient imaging (Fourier) data to reconstruct complex images of a broad range of astrophysical sources. Alternative and simpler three and two telescope designs emphasizing nulling and spectroscopy also were investigated and will be discussed. The culmination of the design process was a simplified two-telescope design, which was called the “C” design, and this is the design that has been studied in the greatest detail.

Several papers have been published or are in press concerning various aspects of the FKSI mission design process [9,10], and in particular a very careful and thorough analysis of the detection of the extrasolar giant planets with FKSI was published recently [11]. A discussion of the requirements formulation and dynamic jitter analysis is in a companion paper in these proceedings [12].

2. DESIGN PROCESS

Initial design studies for the FKSI mission were performed with the Instrument Synthesis and Analysis Laboratory (ISAL) and the Integrated Mission Design Center (IMDC) at NASA’s Goddard Space Flight Center. The A, B, and C designs were based on the preliminary ISAL and IMDC designs, but with a larger design team dedicated specifically to the FKSI mission. The goal of the process was to develop a mission that was exciting to the science team, centered around planet detection and imaging interferometry, but was practical, with a minimum of risk, and at a cost within an expected Discovery cap.

Over the course of approximately eight months our team went through three major design cycles, producing Designs A, B, and C. Costs were estimated using a grass roots approach using a NASA Work Breakdown Structure (WBS) with full cost accounting methods used for all aspects of the mission. These costs were compared with estimates using the parametric PRICE H models. In all cases costs estimated with both approaches were in reasonable agreement, roughly at the 5-10% level.

3. DESIGN “A”

Our initial design “A” with parameters displayed in Table 1 was a fully capable mission with imaging interferometry with five 1 m diameter afocal telescopes at 40 K, and with a sunshade that permits a ± 20 degree Field-of-Regard (FOR) relative to the ecliptic (or cone half- angle relative to the anti-sun line). In addition to a science camera, which could be used for planet detection as well as general infrared astrophysics, this design also featured the option of planet detection using Bracewell nulling on two different baselines, thereby allowing planet detection simultaneously at two distinct spatial resolutions. This design covers the full 5-28 μm band available with Si:As detectors, such as are planned for the James Webb Space Telescope (JWST). This concept closely follows the community desire for a broad based TPF mission as discussed in the National Academy of Science Astronomy Decadal Survey [13], and would be an excellent pathfinder mission for TPF and its European counterpart, the Darwin mission. This concept is fully redundant in its scientific capabilities as planet detection could be done with the imaging system and imaging could be done in a limited way with the nulling subsystem.

	A - Design	B - Design	C - Design
Key Requirements			
Mission Life (on station)	5 years (science operations)	1 year (science operations)	2 years (science operations)
Science Capability	Imaging, Nulling	Imaging, Nulling	Nulling
Science Wavelength Range	5.0- 28.0 microns	5.0 – 28.0 microns	3.0 – 8.0 microns
Science Viewing Angle	+/-20 deg off ecliptic	+/-10 deg off ecliptic	+/-18.5 deg off ecliptic +/-7.5 deg within ecliptic
Observing Rotation Rate	1 rev/hr (max)	0.5 rev/hr (max)	2 rev/hr (max)
Science Data Collect Rate	148 Gb/day (normal mode)	61 Gb/day (normal mode)	1.1 Gb/day (normal w/o margin)
Instr. Thermal Stability	1K/day	1K/day	1K/day
Science Detector Temp	6K (max)	6K (max)	35K (max)
Near IR Detector Temps	30K (max)	77K (max)	77K (max)
Phase B Start to Launch	54 months (no margin)	46 months (no margin)	61 months (incl. 6 mo. margin)
Key Configuration Aspects			
Science Telescopes	5	3	2 (mounted inboard)
Instrument Elements	AT, FT, FTS, (Nuller)	AT, FT, R=10,000 FTS, (Nuller)	AT, FT, Nuller, R = 20 max dispersive element
Interferometer Type	Fizeau (image plane)	Fizeau (image plane)	Michelson (pupil plane)
Boresight Separation	20 m (four-fold boom)	16 m (four-fold boom)	12.5 m (two-fold boom)
Cryocooling	Two 6K ACTD coolers (Low TRL) & (4) 40 K coolers	6K cryostat (H ₂ Dewar) + (2) 30K coolers (IM/near IR detect)	One 32K cooler, near IR detectors passively cooled
Sunshield Location	On Bus	On Bus	On Instrument Boom
Propulsion System	Hydrazine / He Cold Gas	All Hydrazine	All Hydrazine
ACS	6 wheel (Rx + momentum)	Com'l, 4 small Rx wheels	Com'l, 4 medium Rx wheels
Star Trackers	6 Total (4 on instr., 2 on bus)	2 (on bus)	2 (on bus - instr. attitude info passed to bus)
Slew Rate (peak)	0.67 deg/min	0.33 deg/min	Up to 6.1 deg/min (w/3 wheels)
High Gain Antenna Type	2-axis gimbal	Fixed	2-axis gimbal
Ground Contacts	Every 1.0 day (DSN)	Every 1.5 days (DSN)	2x per day (com'l stations)
Instrument Plan/Schedule	Done by Mission Ops Team	Done by Instrument team	Done by Instrument team
Mass, Wet w/contin. (kg)	3,710	3,083	3,183
Power, EOL w/contin. (W)	1,448	1029	766
Fairing Diameter (m)	5	5	4

Table 1. Trade parameter space for Designs A, B, and C. Design A allows for a complete system of 5 telescopes with both nulling planet detection and wide-field high angular resolution imaging throughout the full 5-28 micron band. Design B is an austere design, but it retains 3 telescopes and a capability for imaging but only with a single closure phase. Design C emphasizes nulling with 2 telescopes, and with restricted wavelength coverage from 3-8 microns. This design represents the “science floor” concept.

A block diagram for Design A is shown in Fig. 1, while Figs. 2 displays the basic optical design concept for the imaging system. The synthesized beam pattern (as projected onto the sky) for this design is shown in Fig. 5 of reference 9. This design has the telescopes arranged in such a way as to create “holes” in the beam pattern ~ 0.5 arcsec from the center of the pattern, which have sufficient depth ($\sim 10^{-3}$) for the detection of Extra-solar Giant Planets (EGPs) as well as aperture synthesis imaging. Planet detection and synthesis imaging both require the spacecraft to rotate slowly ($\sim$ once per hour) about the line of sight to the astronomical source.

The optical design utilizes five one meter afocal telescopes that reduce the beam by a factor of 20, as shown in Fig. 2. Next the starlight is brought to an instrument module through a series of static delays to equalize the paths to within a few millimeters, followed by a set of active delay lines that equalize pathlengths to within tens of nanometers, and then a Ritchey-Chretien beam combining telescope.

The optics and instrument are passively cooled to 35K with the aforementioned sunshade, while the science detectors are cooled to approximately 8K. Advanced cryocoolers are used to cool the instrument assembly and the detectors. Two ancillary subsystems are required to make the science camera work, an angle tracking subsystem and a fringe tracking subsystem. The former subsystem tracks target stars at a very high precision (<0.01 arcsec rms) and with a fast response. This system is in addition to a precision ($\sim$ few arcsec rms) tracking camera housed on the spacecraft bus. This system takes out low amplitude residual high-frequency jitter from the spacecraft bus as well as

larger amplitude low-frequency residual pointing errors from the camera on the spacecraft bus. The fringe tracking subsystem also has a fast response and is used to stabilize the rest of the instrument from low-amplitude high-frequency residual spacecraft jitter and larger amplitude low frequency delay errors from residual pointing errors.

Fig. 1. Schematic diagram of Fourier-Kelvin Stellar Interferometer (FKSI) initial Design “A”. This concept utilized a non-redundant linear array of 5 passively cooled telescopes. Near-infrared star light is used to phase the array, i.e., maintain zero optical pathlength difference for star light, while science data are taken with a separate mid-infrared camera and nulling instrument.

simplified to include only hydrazine instead of a two propellant system as in Design “A”. This design retains both imaging and nulling capabilities, but the imaging is significantly reduced because of the loss of two telescopes, allowing visibility measurements on only three simultaneous baselines and a single closure phase, compared to 10 baselines and 6 closure phases for Design “A”. The boom length is also reduced so that a maximum baseline of only 16.5 m is provided, giving a modest loss in angular resolution for the interferometer. Overall, Design “B” retains many of the essential features of Design “A” but with reduced capability and cost.

Design “B” was important to our design process as it helped clarify many of the cost and risk issues. Rather than discuss further trade-offs between Designs “A” and “B” we continue on to describe our “science floor” design, Design “C”.

5. DESIGN “C”

The final design “C” presented here is based on a more radical reduction in scope from Design “A”. The mechanical layout concept for this design is shown in Fig. 4. An additional telescope is eliminated, so that only the minimum of two are provided, hence no Fizeau imaging capability is retained. Instead this design is focused on nulling detection of Extra-solar Giant Planets and on low resolution spectroscopy of their atmospheres. With

Details of the mechanical layout are described in the figure caption. Note that the sunshield shown in Fig. 6 provides only for a ± 20 degree Field-of-Regard (FOR) relative to the anti-sun line. A much larger FOR, e.g., ± 45 degree can be provided with a more advanced sunshade design. Note the large separation between the sunshade and the optical truss holding the telescope. This separation is an essential feature of the design and is required for the truss and telescopes to cool to $\sim 35\text{K}$.

Other detailed features of Design “A” shown in Table I will be published elsewhere.

4. DESIGN “B”

Design “B” is a variant of Design “A” having three telescopes instead of five and a reduction in FOR to ± 10 degrees. Other major changes include elimination of advanced cryocoolers for the detectors and replacement with a solid H_2 cryostat. The detection system now uses NICMOS style detectors operating at 77 K for the fringe and angle tracking subsystems. The propulsion system is

Fig. 2. Concept for Design A optical layout. In this design a wide-field of view is maintained by demagnifying the input pupil (5 afocal 1 m diameter telescopes on a 20 m maximum baseline) by a factor of 20, and a 1 m Ritchey-Chretien telescope is used as a beam combiner.

Fig. 3. Mechanical layout for Design A. Five telescopes are installed on a 20 m truss structure. Not shown are radiation shields around each telescope. The truss has two folds to enable the interferometer to fit into a 14 m long 5 m diameter fairing of a Delta IV launch vehicle.

lower temperature version of the cryocooler used in the refitting of the NICMOS system at the last HST servicing mission. The cryocooler chosen is expected to contribute essentially no measurable vibrational noise to the spacecraft bus.

Design “C” retains a fringe and an angle tracker as in the previous designs. For a nulling interferometer, the null depth requirement (10^{-4}) drives the requirements for the optical components as well as the residual pathlength jitter and pointing requirements. One important trade-off is related to the precision of the optical components versus the use of wavefront clean-up techniques, for example, by the use optical fibers, pinholes, or other techniques. A very high Strehl ratio is required to achieve an adequate null depth, and wavefront clean-up techniques are an important option, but these techniques can significantly lower the throughput of the system. Typically the throughput of an interferometer is low, on the order of a few percent, due to the large number of optical surfaces (typically 30) between the entrance aperture and the detector. Detailed studies of these issues are underway. Discussion of the complete error budget for this design including the above trades is beyond the scope of this paper and is presented in the paper by Hyde et al in these proceedings [12].

Our group has also been actively engaged in the study of detectability of EGPs based on the parameters of the “C” design. A numerical code in IDL has been developed to model the response of the FKSI system including contributions from exo-zodiacal dust, photon noise, pathlength jitter, read noise, and dark current noise. The modeling code uses the measured parameters for the known EGPs and simulates an observation. A preliminary result from this code is shown in Fig. 8 for 55 Cancri demonstrating the viability of planet detection with FKSI. A paper has been recently published describing some of the results of these studies [10] and a more comprehensive paper will be published later this

this reduction in scientific scope, this design is much simpler than the other two. A reduction in the operating band pass from 5-28 μm to 3-8.0 μm was also chosen. This allows for a large increase in telescope and boom temperature from 35-40K to 63K, without a decrease in sensitivity, as can be seen in Fig. 1. In addition, other major changes include reduction in telescope diameter from 1 m to 0.5 m, and a change in detector technology to higher temperature ($\sim 35\text{K}$) long-wavelength ($\lambda_{\text{cutoff}} = 8.5 \mu\text{m}$) HgCdTe detectors that are being developed for JWST.

The boom length is also shorter; now the baseline is 12.5 m. The new center of the bandpass at five microns is approximately half that of the previous designs, which means the spatial resolution is approximately the same as before even with the shorter baseline. The shorter booms and the smaller telescopes in this case allow FKSI to fit into the smallest Atlas V launch vehicle, with only a 4m fairing.

A cryocooler is retained, but in this case we selected a

Fig. 4. Mechanical concept for FKSI Design C with system fully deployed. This design is focused on nulling interferometry for Extra-solar Giant Planet detection and low resolution spectroscopy of the atmospheres of these planets.

Fig. 5. Simulation of a detection of the planet around 55 Cancri (spectral type G8V) having parameters $M \sin i = 0.84 M_{\text{Jupiter}}$, semi-major axis, $a=0.11$ AU, eccentricity, $e=0.02$, and luminosity, $L_*=0.54L_{\text{Sun}}$. This star is at a distance of 13 pc from the Earth. This simulation assumes a null depth of 10^{-4} , thermal background noise, photon noise, and a residual pathlength jitter of 14 nm (rms).

“A” and three telescope “B” designs. We expect to publish additional findings on the science case for a mission of this type. Given the phasing of the Terrestrial Planet Finder – Interferometer (TPF-I), which is currently scheduled for a 2019 or 2020 launch date, it makes it even more important for the US interferometry community to develop a nearer-term mission to further advance the field and develop a community of trained astrophysicists and engineers who can make the strategic mission a success. It is our hope that the FKSI mission is an appropriate stepping stone on the road to the vision of finding earth-like planets in the habitable zone of nearby stars.

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year. The most important result of the simulations has been that a large number of EGPs are detectable with the FKSI “C” design and low resolution spectroscopy can be done on the brightest of the detected planets. A broad range of ancillary science can also be done with the FKSI and a description of some other possible projects will be discussed in subsequent publications.

6. DISCUSSION

Detailed design studies for the FKSI mission have been performed by our group for three possible designs of decreasing scope, from one with five telescopes that allows high angular resolution imaging and nulling (Design “A”), to a mid-range design with three telescopes and imaging and nulling (Design “B”), and finally a design for nulling and spectroscopy of extra-solar giant planets (Design “C”). We have developed a very detailed understanding of costs and risks, including technical and schedule risks, but due to the confidential nature of some of these results, we have not presented them in this paper. While challenging, the FKSI mission can be achieved well within budgets like those for the new Origins Mission line.

During the next year work on the FKSI mission will be focused on completion of our testbed for the optical and control systems, which will be presented in later publications, additional more detailed simulations of the detection process for the two-telescope “C” design, and analysis of the imaging capabilities of the five telescope

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