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Richard G. Lyon

Exo-Solar Planetary Imaging

We live in exciting times; rapid advances in very remote sensing are likely to make one of the holy grails of modern science a reality, i.e., to detect an Earthlike planet around a nearby star and identify biomarkers. Far from the realm of science fiction, this may become a reality with NASA's Terrestrial Planet Finder (TPF) mission planned for 2015.

Indirect ground-based have discovered greater than 100 exo-solar planets to date. These detections are inferred from Doppler shifts in the source spectrum due to radial velocity variations of the central star believed caused by the planetary mass in motion. Planets found by this technique are biased towards large mass Jupiter-like planets. Earthlike, or terrestrial, planets are unlikely to be found by this technique. Advances in space technology, which include high dynamic ranging imaging, interferometry, mirror technology and optical control systems are likely to make this a distinct possibility in the near future. These techniques are being assessed and new advances are being made by NASA, university and industry teams with the goal of combining them into TPF.

The TPF Science Working Group has provided the main science requirement in a Design Reference Program succinctly as "TPF must detect radiation from any Earth-like planets in the habitable zones surrounding ~150 solar type (spectral types F, G, and K) stars. TPF must: 1) characterize the orbital and physical properties of all detected planets to assess their habitability; and 2) characterize the atmospheres and search for potential biomarkers among the brightest candidates for Earth-like planets." The implications from a systems point of view are: (i) repeatable detections with a SNR of at least 5, (ii) detect planets with from 1/2 to twice the diameter of Earth, (iii) detect planets in the loci of orbits where the central star would allow liquid water to exist on the planet. These requirements drive TPF's size to be 4 to 8 meters in the visible and ~50 meters in the IR. A system operating in the visible would see reflected light from the central stellar source to the planet and some atmospheric absorption lines could be resolved. For a system operating at 0.6 to 3 microns TPF could resolve CH_4, CO_2, H_2, H_2O, NH_3, O_2 lines as well as potentially discriminate some solids and liquids. A TPF from 3 to 8 microns could resolve CH_4, CO_2, C-H, CO, H_2O, N_2O and a long wavelength IR system could resolve CH_4, CO_2, H_2O, NH_3, O_3 plus discriminate some particulates (dust).

TPF is likely to be either a filled aperture telescope operating in the visible or an IR interferometer. A visible light system can be smaller (less than 10 meters in aperture) than a comparable IR interferometer (~50 meters) however advances in mirror technology are required. Mirrors must be ultra-smooth (~wavelength/15,000) to minimize scattered light; in addition active optics would be required to maintain low and mid-spatial frequency mirror structure at acceptable levels. IR interferometry would require either ultra-stable (nanometer scale) large boom technology or formation flying technology with knowledge and/or control to the nanometer scale. Both require daunting technologies, which are only in their infancy. Over the next 3 years (FY03 – FY06) it is expected that significant funding will be available for technology development to bring these technologies up to par for TPF.

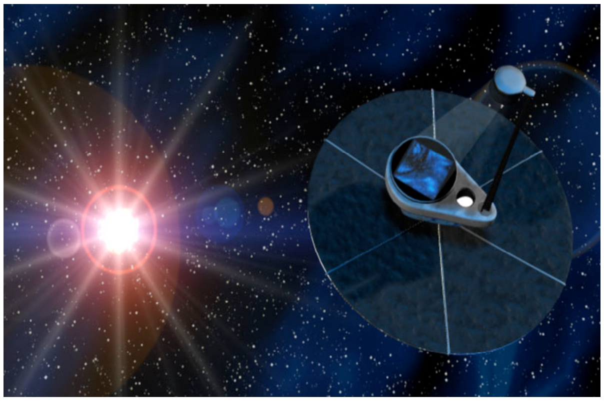

Figure 1-1: *Concept for Visible Light Apodized Square Aperture Architecture for NASA's TPF*

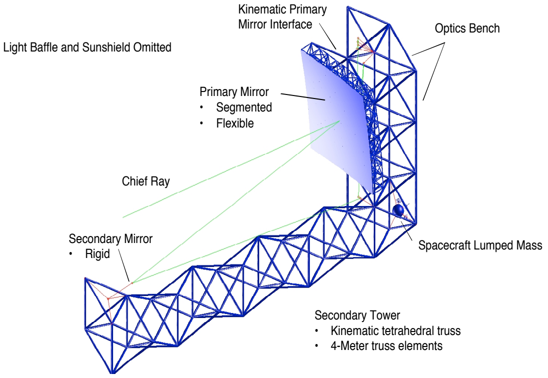

Figure 1-2: *Structural/Optical Model of Apodized Square Aperture for NASA's TPF*

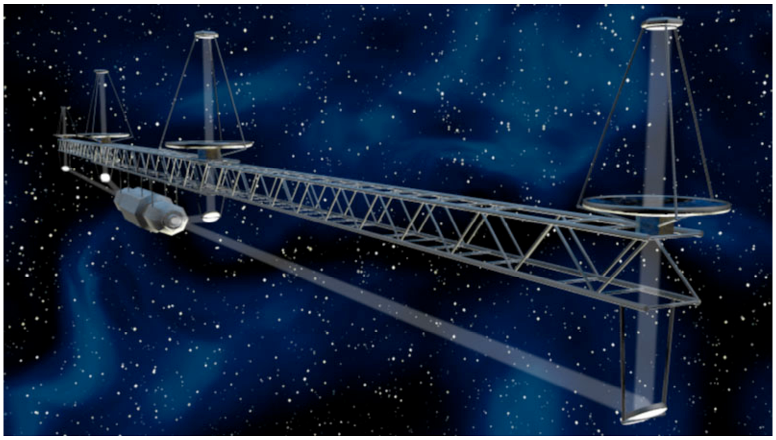

Figure 1-3: *IR Non-Redundant Linear Array Interferometer Concept for TPF*

Space-Based Interferometric Imaging

The Hubble Space Telescope (HST) is the largest space-based astronomical telescope flown to date. Its aperture is 2.4 meters in diameter and is considered *monolithic*, i.e., the primary mirror is a single continuous sheet of glass. It is this monolithic primary mirror, which is the primary driver for weight and cost for HST. Even with a space-based system of this size resolution of stellar disk is impossible, stars still look like points of light. The James Webb Space Telescope (JWST) is likely to consist of a *segmented* aperture telescope, i.e., the primary mirror consists of a set of mirror segments, each manufactured individually and mounted, with minimal spacing, in the same telescope. Segmented telescopes can generally be larger and lighter than monolithic telescopes, however, the segments must be aligned and stabilized to a fraction of the wavelength of light. JWST is likely to be on the order of 7 meters in diameter. Segmented telescopes will generally require an active optical control system consisting of wavefront sensing (to sense the misalignments and deformations) and actuators to move and/or deform the optics to the required shape. Thus the trades between a monolithic and a segmented are weight and size versus system complexity with segmented systems being more complex. However, segmented systems still will not resolve an individual star. If we move the segments apart by a significant fraction of their width we have an interferomtric imaging system, i.e, an interferometer. Interferometers for imaging generally consist of two types, a Fizeau interferometer or a Michelson interferometer. A Fizeau interferometer consists of an array of sparsely separated segments, which have a common focus. A Michelson interferometer generally consists of an array of sparsely separated segments of which the beams are reduced in size then mixed together with phase delays. A Fizeau has spatial fringes on a 2D detector while a Michelson consists of temporal fringes. Algorithmic techniques are used to demodulate the fringes and to reconstruct an image. Imaging interferometry could in principal be done in space with either an array of separate telescopes mounted on a large boom or by an array of individual telescopes flying in formation. An array of formation flying spacecraft spread out over a few hundred meters in space could resolve the structure of individual stars around the nearest stars and could conceivably detect and image planets. Formation flying systems require technology development in the areas of complex control systems, ranging, metrology, wavefront sensing, optical control, on-board computing. An array of telscopes coupled together on a boom will also require, complex control systems and an ultra-stable platform to the nanometer level. Some of the issues which are under study are knowledge versus control ? i.e. if we have knowledge and misalignment can we correct for in the software processing or do we need to actually move servos/actuators to compensate, or indeed does the platform actually need to be stable to these levels. There are complex questions, which can be answered by full systems simulations.

NASA has been studying imaging interferometry and studying potential science missions such as Stellar Imager (SI), Sub-millimeter Probe of the Evolutionary Cosmic Structure (SPECS) and Fourier-Kelvin Stellar Interferometer (FKSI).

Optical Systems Characterization and Analysis Research Software

Space-based imaging generally require a number years of design and analysis, prior to fabrication, assembly, integration and launch. During ground testing, known as *integration and test*, predictive modeling is required. Following launch, performance assessment and calibration is required; also validated models need to exist to debug the system. During the design of algorithms and software realistic models must exist to simulate data to test and validate data processing algorithms, as well as on-board control algorithms. For past systems multiple vendors supplied software packages have been used. However, these packages generally do not allow for ease of modeling of segmented and interferometer systems nor for wavefront sensing and optical control systems, also, they generally do not have the fidelity to adequately model systems to the nanometer level. The Optical Systems Characterization and Analysis Research (OSCAR) software is being developed to optically model just such systems.

OSCAR has, and is currently, being developed by NASA to assist in the design and analysis of large space-based imaging systems. Systems of this type require large scale, high-fidelity optical modeling. The large number of node points utilized generally requires parallel computers. OSCAR runs on a Beowulf cluster. To facilitate parallel computing OSCAR is written entirely in "C" with message passing interface (MPI)[1]. MPI is a standardized set of libraries, which allow communications, data passing and computing across a many node Beowulf cluster.

OSCARs legacy is traceable to the post launch phase retrieval work[2,3] to determine the source of the error on the Hubble Space Telescope and has been utilized to accurately model the optical point spread functions[4] (PSF) to facilitate science observations[5,6]. OSCAR has been significantly enhanced over the past 15 years to include capabilities for modeling segmented aperture[7,8], interferometric imaging[9] and coronagraphic modeling[10,11,12]. OSCAR has been used on the Next Generation Space Telescope (NGST), now the James Webb Space Teles,cope (JWST), Sub-millimeter Probe of the Evolutionary Cosmic Structure (SPECS), Terrestrial Planet Finder (TPF), Advance Geophysical Satellite (AGS), JWST Multi-Object Spectrometer, Stellar Imager (SI), and Earth Atmospheric Solar occultation Imager (EASI).

OSCAR includes the capabilities to model monolithic, segmented, interferometric and coronagraphic systems. It includes optical misalignments, deformations, residual aberrations, low-, mid- and high-spatial frequency aberrations, multiple diffraction models, polychromatism, raytrace, scattering, apodization, jitter, scene modeling, detector effects, noise and different sampling models. OSCAR also simulates wavefront sensing such as phase retrieval, phase diversity, maximum entropy deconvolution[13], and closed-loop optical control with actuators and deformable mirrors[14]. OSCAR is currently being integrated with a specialized graphical user interface, which will allow remote use over the web in a client server model, where the client will run remotely and the software will be served up a local Beowulf cluster. OSCAR is based on a *tree structure,* which allows OSCAR prescriptions from multiple vendors to be easily and quickly integrated together. For example, if one vendor supplied an OSCAR prescription for the telescope, another for the active optical bench and yet another for the instrument(s), then it is trivial to integrate them together in OSCAR. Thus arrays of identical spacecraft flying in formation are easily integrated once a prescription for one is developed.

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