Interferometer Designs for the Terrestrial Planet Finder

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Abstract. The Terrestrial Planet Finder (TPF) is a space-based infrared interferometer that will combine high sensitivity and spatial resolution to detect and characterize planetary systems within 15 pc of our sun. TPF is a key element in NASA's Origins Program and is currently under study in its Pre-Project Phase. We review some of the interferometer designs that have been considered for starlight nulling, with particular attention to the architecture and subsystems of the central beam-combiner.

1. Introduction

As a part of its long-term goals, NASA has been investigating the feasibility of using space-borne infrared interferometers for the detection of neighboring planetary systems. The technology Road Map described in the *ExNPS Report* (Beichman 1996) was written specifically to support the development of this interferometer, which in 1997 became known as the Terrestrial Planet Finder (TPF). Here we outline several design considerations for TPF and expand upon material included in the *TPF Book* (Beichman, Woolf, and Lindensmith 1999).

The European Space Agency has also been funding studies to evaluate an infrared space interferometer (IRSI) for direct planet detection, with goals similar to those of TPF. ESA's ongoing studies are relevant to TPF but will not be described here (see for example Mennesson and Mariotti 1997; Ollivier and Mariotti 1997; Robbe 1999; and Mennesson and Léger 1999).

2. Array Design

The interferometers that have been designed to directly detect planets have all been derived from the concept of a nulling beam combiner, originally suggested by Bracewell (1978) and also described by Bracewell and McPhie (1979). Concepts for the design of the Terrestrial Planet Finder have more recently been based on studies by Angel and Woolf (Angel and Woolf 1997; Woolf and Angel 1997; Woolf 1997; Woolf *et al.* 1997). Principal among these has been the OASES design (Angel and Woolf 1997) and a proposal for a smaller precursor mission named PDI (Woolf *et al.* 1998).

The design concepts for TPF have changed substantially in the last few years and presently include strategies to suppress time varying noise sources and to suppress the bright symmetric emission from a zodiacal cloud that might surround a planetary system. Woolf *et al.* (1997) reasoned that not only does

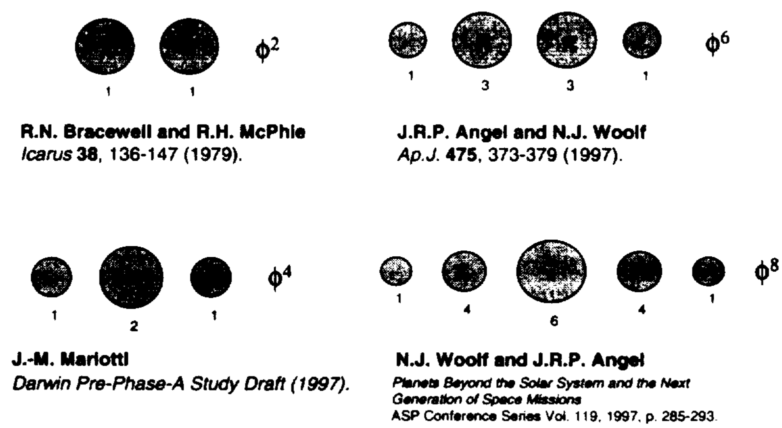

Figure 1. Linear nulling arrays. TPF has been conceived as an array of two or more nulling interferometers that are each phased with respect to each other. This allows the far-field response to be modulated or chopped, while maintaining a null on the star. The possible component nulling interferometers are shown here along with their null depth (after Woolf and Angel 1997).

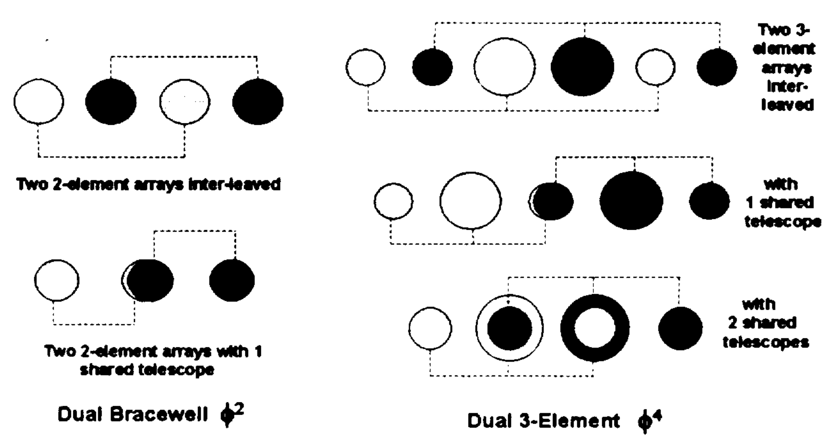

Figure 2. Dual Linear nulling arrays. Pairs of nulling interferometers can be combined in various ways to allow the rejection of unwanted noise sources. The simplest method is to inter-leave the array elements as shown. Combinations are also possible where one or more telescopes are shared between the component sub-arrays.

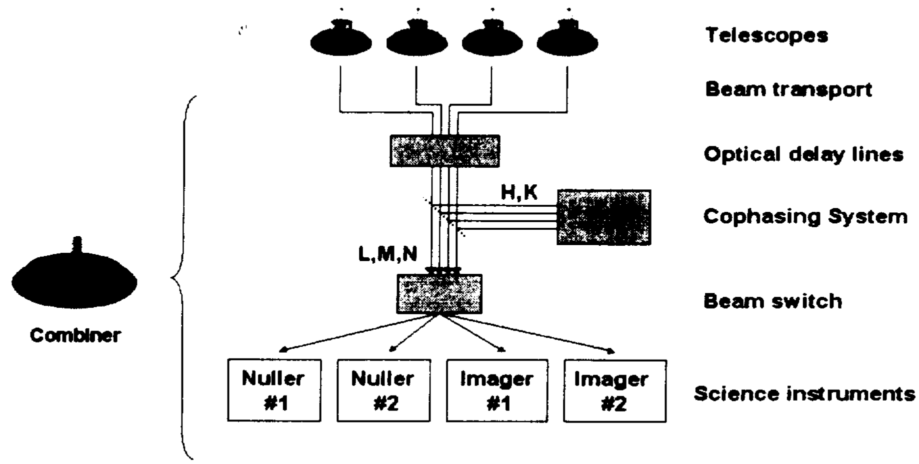

Figure 3. Modular design of the TPF beam combiner. Using four telescopes in a linear array, there are a number of possible beam combinations: the null depth can vary as field angle, ϕ^2, ϕ^4, or ϕ^6, depending on how the light is divided and combined from each telescope. Using a modular design, as illustrated here, the interferometer could be reconfigured from one mode to another to optimize the array for each target source.

the array have to provide a deep and wide null superimposed on the star, but it must also be able to phase or modulate its response around the target star. New designs for nulling interferometers are therefore based on super-arrays composed of two or more sub-arrays of nulling interferometers. The component arrays of these super-arrays are the simply the designs for two, three, four, or more-element nulling interferometers, as shown in Figure 1. The simplest four-element chopping array uses two interleaved two-element nulling interferometers, of a type suggested by Bracewell and McPhie (1979). This and other possibilities of constructing subarrays are shown in Figure 2.

3. Modular Design of a TPF Beam Combiner

For the purpose of illustrating the feasibility of the TPF mission, a design was chosen based on a four-element linear array (Beichman, Woolf, and Lindensmith 1999). If we limit the number of available telescopes to four, we must then decide how to partition the light amongst sub-arrays, knowing that we will better suppress the starlight if there are more elements in each sub-array. We therefore arrive at a performance trade-off between the ability to provide a deep and wide null to suppress starlight and the ability to modulate the nulled response.

Although this limitation would exist with any one configuration, it is possible to design TPF with the ability to reconfigure its beam-combining optics through an exchange of combiner modules. With four telescopes in a linear array, there are a number of possible beam combinations: the null depth can vary as field angle, ϕ^2, ϕ^4, or ϕ^6, depending on how the light is divided and combined

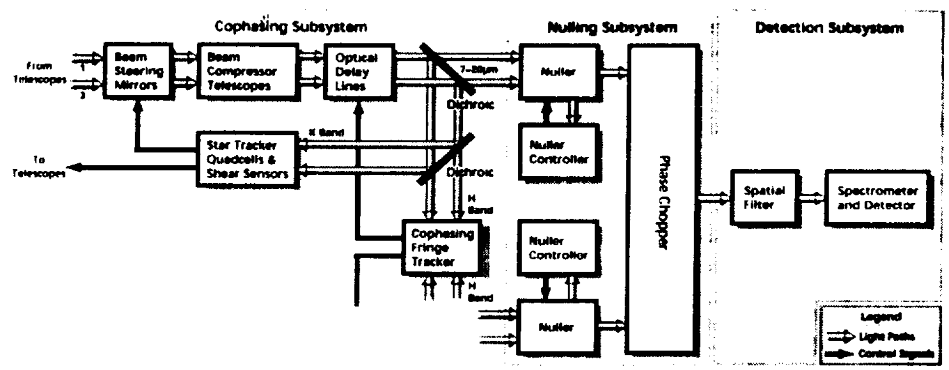

Figure 4. Expanded view of a beam combiner for TPF, showing the components of the cophasing subsystem, a nulling subsystem for a dual-Bracewell array, and a detection subsystem.

at the beam combiner. The instrument could then be configured to optimize the array for each target source. A block diagram showing an overview of this design is illustrated in Figure 3. Further details of the cophasing system are shown in Figure 4.

4. Delay Compensation

The present concept for TPF is a linear array using a separate combiner spacecraft and four 3.5 m diameter free-flying telescopes. The simplest arrangement for delay compensation would be to place the telescopes at even spacings along the surface of an imaginary parabola and to place the combiner at the parabola's focus, as illustrated in Figure 5. If the parabola is pointed in the direction of the star, the delay compensation is performed as if the light were focused from a giant monolithic mirror. The disadvantage of this approach is that the thermal design becomes more complicated; the telescopes must each guard against sources of thermal noise and be passively cooled to ~35 K. The combiner and certain telescopes near it will however appear in the foreground of telescopes further down the parabola; the heat shields that cool the combiner will now be reflecting sunlight and radiating in full view of these telescopes.

An alternate design, shown in Figure 6, is to place all the telescopes in a plane perpendicular to the direction of the target star. This is the current design concept for TPF. The delays can then be provided by routing the starlight from one telescope to another before sending it to the combiner, as illustrated in Figure 6. In this case all the sun shields lie in the same plane, simplifying the thermal design. However, by routing the starlight from one telescope to another we may overly constrain the control laws of the telescopes (Lund, 1999). Notice that if we were to move telescope 3 in Figure 6, it would change the delays from telescopes 2, 3, and 4. It is currently not clear which scheme of delay compensation would best enable planet detection.

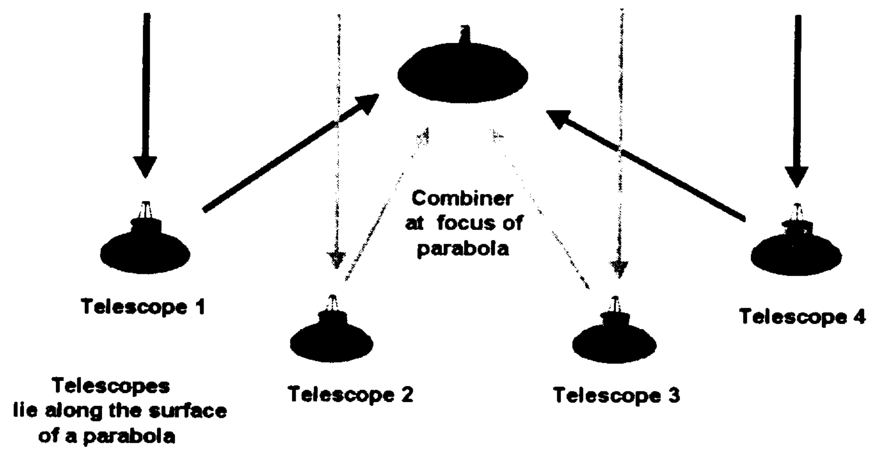

Figure 5. Delay compensation along the line of sight to the star. Output beams from telescopes are given equal delays by placing telescopes along the curve of a parabola with the beam combiner positioned at the focus. This is the method of delay compensation currently being envisaged for the Darwin/IRSI mission.

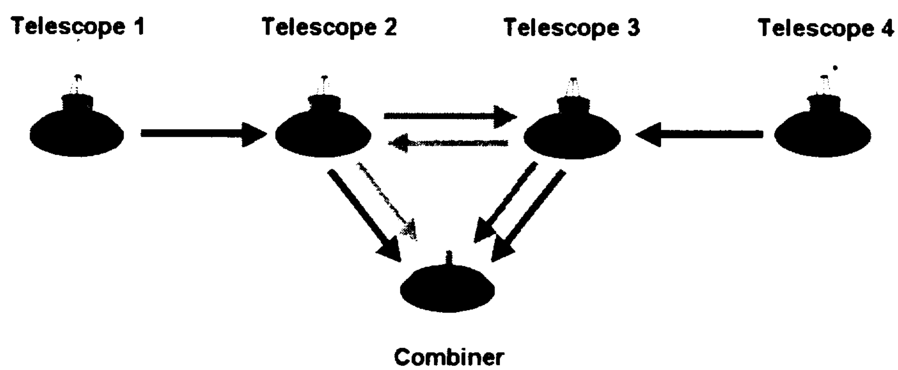

Figure 6. Delay compensation in the plane of the array. Output beams from telescopes are given equal delays by sending them to neighboring telescopes prior to sending them to the beam combiner. This method of delay compensation is the one currently envisaged for TPF.

5. Conclusion

Further work is in progress to evaluate the best options for TPF. Its ultimate design will depend on the results of these ongoing studies and on knowledge gained from experience with other stellar interferometers presently in development.

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