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NEW LINEAR NULLING ARRAY CONFIGURATIONS

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Planet Finder Options I: New Linear Nulling Array Configurations

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Abstract.

Planet Finder is a nulling interferometric mission in space to study extra-solar planetary systems. In this paper we show new options for symmetric linear nulling arrays. Of special interest are arrays with quarter wave phase shift between adjacent elements, which yield bright fringes that are strongly asymmetric about the very deep null used to suppress the starlight. When the signals from the rotation of such an array are subject to cross-correlation analysis (similar to aperture synthesis), the resulting images are free from the 180 degree ambiguity of earlier nulling interferometers. The new array configurations can be operated also as a powerful interferometer for conventional astrophysical imaging.

1. Use of a Nulling Interferometer

A linear nulling interferometer capable of imaging planetary systems and obtaining individual planet spectra for planetary systems has been described by (Angel &Woolf 1997). The interferometer places a set of parallel transmission fringes onto the plane of the sky, with a null on the star whose planets are to be studied. The interferometer is rotated like a propeller about the axis to the star, and the fringes rotate about the star. Each planet produces as signal, a set of maxima whose widest separation occurs when the interferometer position angle is 90 degrees from the planet position angle. When several planets are present, the resulting complex modulation of signal with rotation angle can be deconvolved to yield an image of the system. Because the fringe spacing is proportional to wavelength, the different wavelengths need to be separated in the study, and so the observation will also yield the separate planet spectra.

In the first version of the planet finder two problems surfaced. First, a zodiacal dust cloud would yield a signal that resembled a close-in planet, and though the planet would be distinguished by its motion, that would take time to resolve. Secondly, the images from deconvolution have a 180 degree ambiguity in the planet position angle. This could be resolved by making the center of the fringes precess closely around the star, but with poor sensitivity. In this paper, both of these difficulties are resolved in an optimized way.

2. Why Use a Linear Array?

Two dimensional arrays were first considered by (Angel 1990), and have been further discussed (Leger et al. 1996). The advantage of a linear array rather than a 2-dimensional array is that a 2-D array has a 2-D transmission pattern. For a 2-D pattern, the average transmission of a given source will be substantially affected by its radius relative to the pattern center. For a given source, the efficiency of the device will vary with wavelength, and will vary differently for each source. Thus there will be a loss of efficiency for obtaining spectral information about the planets, and since this is the most demanding task of the device (in required exposure time), that is a significant drawback. Much smaller changes occur with a linear array, most planets will pass through fringes of complete destructive and constructive interference.

3. Inadequacy of a Bracewell Pair for Studying Earth-like Planets

Linear nulling arrays differ in their ability to suppress the radiation of a central star. The minimum spacing of a Bracewell pair (two elements out of phase) studying an Earth-Sun-like system is set by the need for the closest maxima to be within the Earth's orbit, so that in a rotation the Earth signal will produce four blips. But the null of the interferometer has a transmission that increases with radial distance from the center as $sin^2\ \phi$, or approximately as ϕ^2. Thus since the star's semi diameter is 1/200 AU, the transmission of the limb of the Sun is at least π^2 / ($200^2 * 4$) or about 10^-4. If we require one interferometer to resolve 1AU with a range of 5 in the angular spacing of the star and planet, then the transmission for the nearest stars will be 25 times worse, or about 1 part in 600. Of perhaps even greater concern is that any slight jiggling of the null center while in use, will likely cause large fluctuations in the starlight leaking through, and this will swamp the planet signal, typically about 10^{-7} of the star signal in the IR.

4. Multiple Element Arrays With Better Nulls

To solve the above difficulty, broader deeper nulls can be obtained from linear arrays with more than two elements, in which beam combination is made with achromatic phase shifts of a half wave between elements. Symmetrical linear arrays fall into two families according to whether there are an odd or even number of elements. Figure 1 shows the first two members of these two families and the power of the null. The ϕ^6 power 4-element array was discovered by Angel, the ϕ^4 power 3-element array by Mariotti, and the generalization by Woolf (intensities like the factors of $(1+x)^n$).

In figure 1, the numbers above each array element shows its diameter and the signal amplitude for it, and the numbers below show the phase of that element in waves. The element-to-element spacing is identical, and all of these arrays have the same separation of the first maximum from the star, though the angular resolution increases slowly with the number of elements.

All these arrays as shown have totally constructive interference at the maxima. In the system shown by (Angel & Woolf 1997), a system operating without

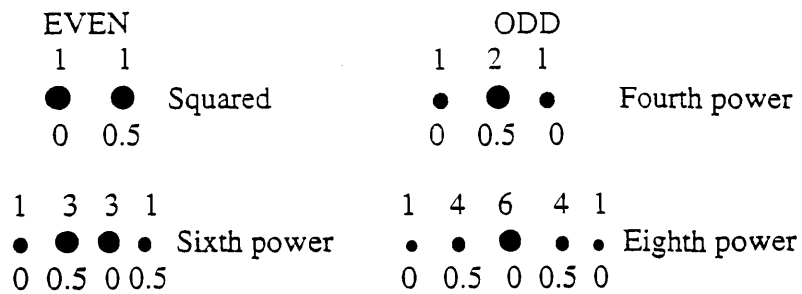

Figure 1. Simple linear arrays. This diagram shows the arrangement of equally spaced mirrors in nulling arrays. The amplitude (and diameter) from each mirror is shown by the number above it (and qualitatively by the size of the circle). The phase in wavelengths is shown under the mirror. The power associated with each array is the way that its contribution to the intensity in the diffraction pattern decreases with the off axis angle of a source. For example, for the 3-element array the intensity is proportional to the fourth powerof the off-axis angle.

total constructive interference was shown because it is possible to shorten the array this way, but is not optimum use of the collecting area. At 10 μm wavelength a 10 m length produces fringes 0.1 arcsec from the origin. Thus for planets separated from their star by at least 0.05 arcsec, a single 3-element device is 40 m long, and a single 4-element device is 60 m long.

Figure 2 shows a comparison of the nulls of all arrays in the table above. Each array has the same spacing of elements and the same fringe spacing. For the 4-element array, a transmission of 10^{-6} is achieved at about 1/15 the distance to the first maximum. For the 3-element array it is about 1/50 of that distance, and for the Bracewell pair it is about 1/3000 of the distance. If we consider main sequence stars to have the same size, then the 3-element array is just about useable over a distance range of 4:1, which is perhaps marginally adequate for a first generation mission. The 4-element array is useable over a range of 12:1, and is distinctly more versatile, though at the expense of being somewhat longer for the same resolution on the sky. Both nulls can be broadened about 50% by minor amplitude adjustments. A difficulty with the configurations of figures 1 and 2 is the symmetric nature of the fringes about the null. It leads to a 180° ambiguity in reconstructed images, with every planet appearing twice.

5. Double Arrays

A "super array" whose individual elements were themselves nulling interferometers could be operated in the normal mode of imaging aperture synthesis, without

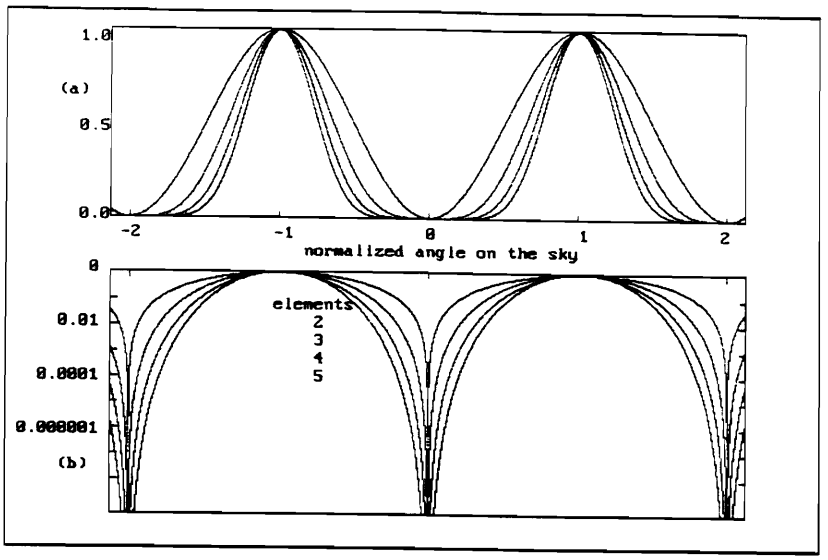

Figure 2. Transmission intensities from simple linear arrays. This shows the intensities in both linear and logarithmic scales for the intensities contributed to the diffraction pattern for arrays with two through five elements. Notice how the null becomes broader and deeper as the number of array elements is increased.

restriction in the phase differences used in beam combination, and with no 180 degree ambiguity in the reconstructed image. To maintain a high amplitude of interference between the two arrays, they should be identical. Such arrays have been suggested by Shao, (Shao 1996), with the possibility of obtaining images of very high resolution. We note though, that they will not allow detection of very close-in planets because those are excluded by the broad nulls of the individual arrays. Also, higher resolution can quickly lead to very large super array sizes, given the 50 - 100 m scale of the individual nulling sub-arrays.

Here we explore the possibility of placing two nulling arrays very close together, with their elements interdigitated. This gives no substantial change in resolution, but completely eliminates the imaging ambiguity mentioned above. This is particularly important to distinguish close-in planets from elliptical zodiacal dust clouds. Configurations of doubled 3 and 4 element arrays are shown in figure 3. The light from alternate elements is first combined with achromatic half wave phase differences. The null outputs of the alternated nulling arrays are then combined at a simple symmetric 50/50 beamsplitter, whose two outputs have achromatic phase differences of 1/4 and 3/4 wave. Such arrays produce highly asymmetric fringe patterns. Figure 4 shows the null pattern for the 8-element array of figure 3. Note that the fringes are one sided. Figure 6 shows an extended view of the fringe pattern.

6. Chopped Output Pairs

The two interferometer outputs show the same pattern, but mirror imaged. Thus if the two interferometer output signals are subtracted, the response of the interferometer consists of alternating positive and negative fringes, as in figures

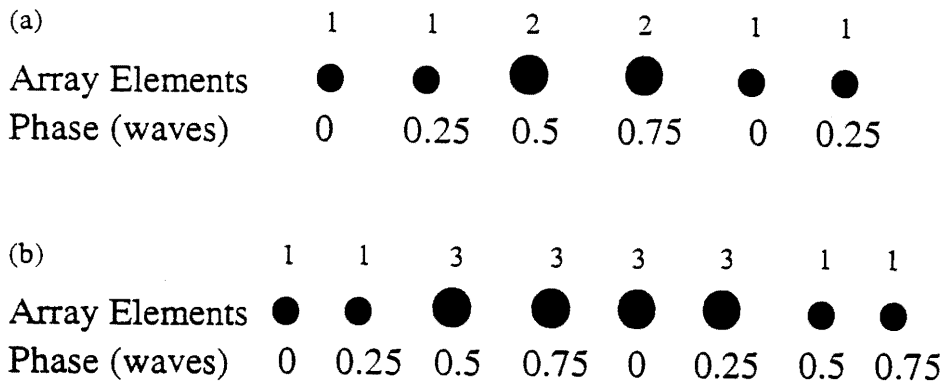

Figure 3. Paired linear arrays. This diagram shows how three and four element arrays from figure 1 can be combined with a second similar phase shifted array by staggering the elements. The phases are shown under each element.

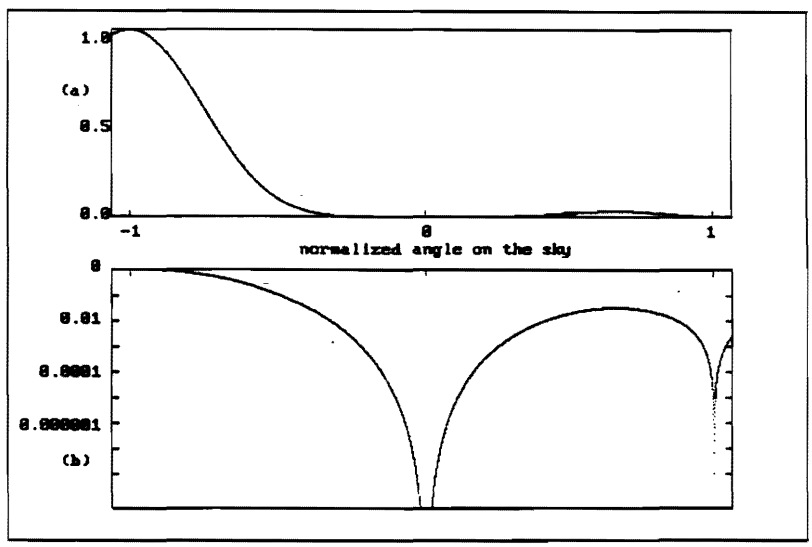

Figure 4. Eight element paired array transmission.The asymmetric transmission pattern of the eight element array is shown. Note that the interference peak at -1 is preserved, while that at +1 is completely suppressed. As a result of this, there is no ambiguity in the position of an observed planet. The result is shown for exact amplitudes of figure 2. Optimum breadth of the null would be obtained by having the smaller elements with a 4% reduction in the amplitudes they contribute.

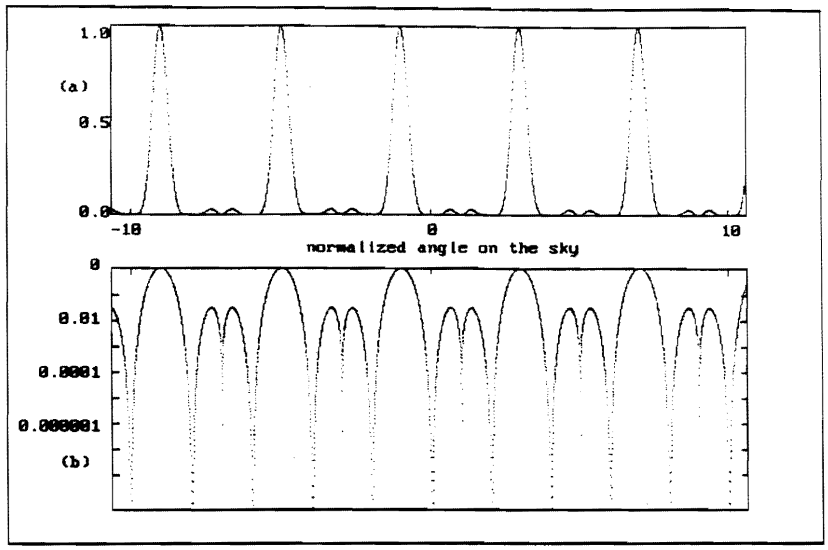

Figure 5. Eight element paired transmission, extended view. This figure shows how the pattern of figure 4 extends across a ten-fold larger area of sky.

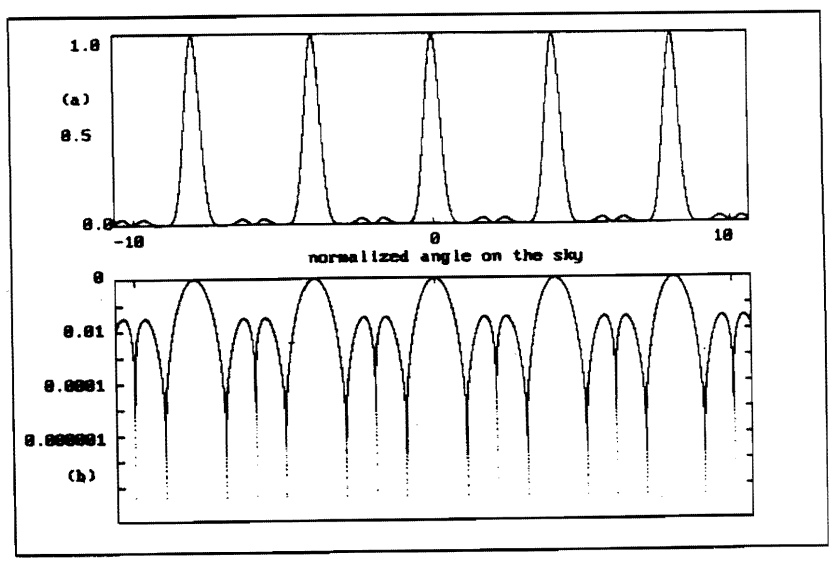

Figure 6. Array arranged for general astrophysical use. This shows how the eight element array adapted for astrophysical use. The figure is the transmission pattern of figure 5 with a principal maximum shifted to be on the central position. This is accomplished by having all the elements in phase.

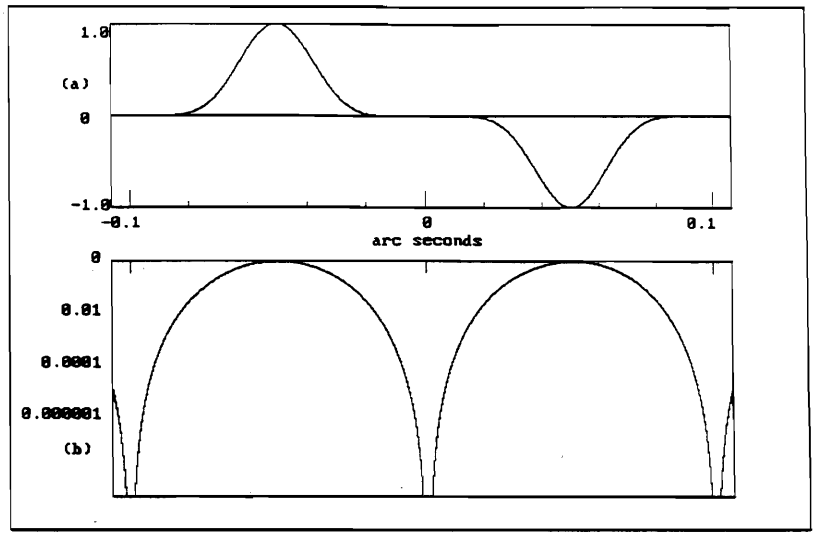

Figure 7. This shows the effect of chopping the two outputs of an 8-element paired array. The positive and negative going transmissions will cancel out for any symmetric radiation, such as the symmetric component of exo-zodiacal radiation. A planet will only produce a single positive image, as in the use without chopping.

7 and 8. Such a signals are insensitive to symmetric zodiacal emission, because for each part of the emission on one side of the star giving a positive signal, there is an equal part on the other side of the star producing a negative and canceling signal (though the photon noise remains).

The planet shows up through the complete rotation of the interferometer, on one side of the star it produces alternately positive and negative signals according to its position. Since both outputs are available all the time, and the signals can go to two detectors, all the light from both of the nulled sub-arrays can be used.

It is notable that the null of the double system broadens because the starlight cancels between the two interferometer phases. (And its photon noise still stays less than exo-zodiacal radiation). The 6-element version can have a null 3 mas diameter, and detect planets as close as 25 mas, giving a total interferometer length of 100 m — though much smaller systems of lower resolutions are possible. The 8-element system for the same maximum star diameter could have a resolution as sharp as 9 mas and still strongly suppress a 3mas stellar disk, but for that would be about 400 m long. This configuration would be very helpful in a second generation instrument observing some of the close planets now being found by radial velocity studies.

7. General Astrophysical Use

For general astrophysical use, all the outputs from the various beamsplitters carry useful information, because deep nulls will not in general be required. There is the possibility of switching to simpler and more direct beam combining

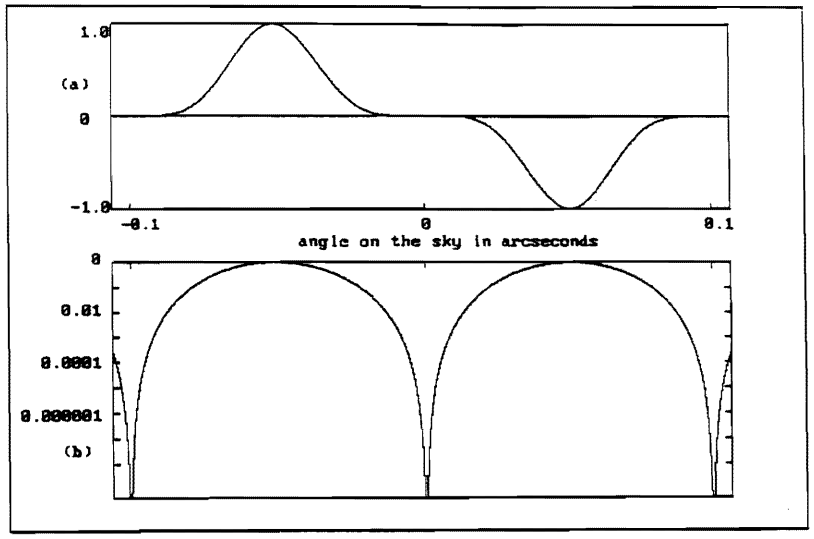

Figure 8. The chopped outputs from a 6-element array. This shows the effect of chopping the two outputs of a 6-element paired array. The positive and negative going transmissions will cancel out here too for any symmetric radiation, such as the symmetric component of exo-zodiacal radiation. A planet will only produce a single positive image, as in the use without chopping. The narrower null than figure 7 should be noted. This configuration would be just adequate for a first mission.

methods, for example to make one of the outputs represent a fan beams with constructive central transmission, as shown in figure 5.

For more general astrophysical use, there is still a need for a star on which to phase and point the system, but since the demands on phase precision drop by a factor of about 50, the star can be much fainter than for planet studies. Although it would be possible to select a set of elements giving a non-redundant array from the planet finder arrays, in practice there does not seem to be any disadvantage in retaining all the planet finder elements.

8. Summary

This paper contains information on the generalization of linear nulling arrays to large number of elements. In the first case, the elements are equally spaced, but the amplitude required decreases with the distance of the element from the center. In the second case, two identical arrays are paired and staggered, with a $\lambda/4$ phase difference between them. The general characteristics of arrays are:

- The closest-in strong transmissions, and thus then closest observable planet spacings are defined by the spacing of nearest elements combined with a half-wave phase difference.
- The null breadth improves relative to the closest in fringe as the number of elements increases.

The characteristics of paired arrays are:

- The width of the null in which to set the star image is set by the component nulled arrays. Thus combining Bracewell 2-element arrays does not seem useful.
- Quarter-wave phase shifts between the two interdigitated component arrays seems to provide best patterns when the sub-arrays are also shifted relative to one another by integer+1/2 increments of the element-to-element spacing.
- Paired arrays with 1/4 wave phase shift eliminate the 180 degree ambiguity in planet position angle.
- The paired arrays can null the signal from the symmetric component of zodiacal dust emission.
- A widely spaced super array of two close-spaced arrays generates close fringes but can not study close-in planets.
- Close spaced fringes require high spectral resolution to avoid fringe smearing.
- The arrays lend themselves to general astrophysical use, when all the interferometer outputs can be used, not just the nulled outputs..

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