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An Adaptive Coherent Optical Receiver Array

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L.B. Mercer

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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AN ADAPTIVE COHERENT OPTICAL RECEIVER ARRAY

L.B. MERCER
Group 67

TECHNICAL REPORT 921

18 JUNE 1991

LEXINGTON MASSACHUSETTS

ABSTRACT

A linear, four-element, adaptive heterodyne optical receiver array employing semiconductor lasers is described. The array adaptively adjusts the phase of each subaperture IF signal to correct for wavefront tilt and distortion and nonuniform optical and RF path delays across the array by phase locking each channel to a reference channel.

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1. INTRODUCTION

Coherent optical radar and communications systems commonly require antenna gains of 120 dB and higher. The expense of building these large diameter telescopes with high quality optics can be prohibitive. RF systems designers have long recognized that it is often advantageous to realize a high gain antenna with an array of antennas. An array antenna offers the opportunity to correct for atmospheric distortion and the possibility of automatic tracking, point-ahead, adaptive nulling, and multiple beams. Another advantage of an array is that an array of N small telescopes will have volume $1\sqrt{N}$ the volume of a single large telescope with the same F-number and total aperture size. The array may be constructed with separate telescopes or it may be formed by placing a detector array in the pupil plane of a larger telescope [1]. Previously such an array was constructed using a Bragg cell as a phase shifter for each channel [2]. Another technique, applicable to receiver arrays, uses electronic phase shifters to adjust the phase of IF signals from each subaperture [3]. An array such as this may prove most useful in nonsymmetric links where the gain of the transmitter antenna can be much less than the gain of the receiver antenna. The system might be a satellite to the ground communications link with a high capacity downlink and a low capacity uplink, or it might be the receiver for a laser radar with a broad illumination by the transmitter and a high resolution requirement for the receiver.

A coherent optical receiver array has been built that adaptively adjusts the phase of the signal from each subaperture using electronic phase-locked loops (PLL). The array effectively provides the signal quality of a receiver with an aperture area equal to the sum of the individual subaperture areas. At the same time the array reduces the tracking and wavefront requirements to those of the smaller subapertures by correcting for wavefront tilt and distortion across the array.

2. SYSTEM DESCRIPTION

To demonstrate the concept of electronic phase adaption, a four-element linear array of coherent optical receivers has been assembled as shown in Figure 1. The individual aperture size is 5.1 mm square providing a full aperture 20.3 mm wide. The combined local oscillator (LO) and signal fields entering each lens are focused onto separate positive-intrinsic-negative semiconductor (PIN) diodes and the resulting first IF signals are amplified before further processing. Another lens with a 5.1×20.3-mm aperture and a PIN detector are located on the other side of the beam splitter to allow simultaneous comparison of the full aperture with the array. This lens has a 5.1×20.3-mm aperture to match the array. The LO and signal are obtained from separate Hitachi 30-mW HL8314E laser diodes operating at 860 nm. The combined IF linewidth for the two lasers is about 30 MHz.

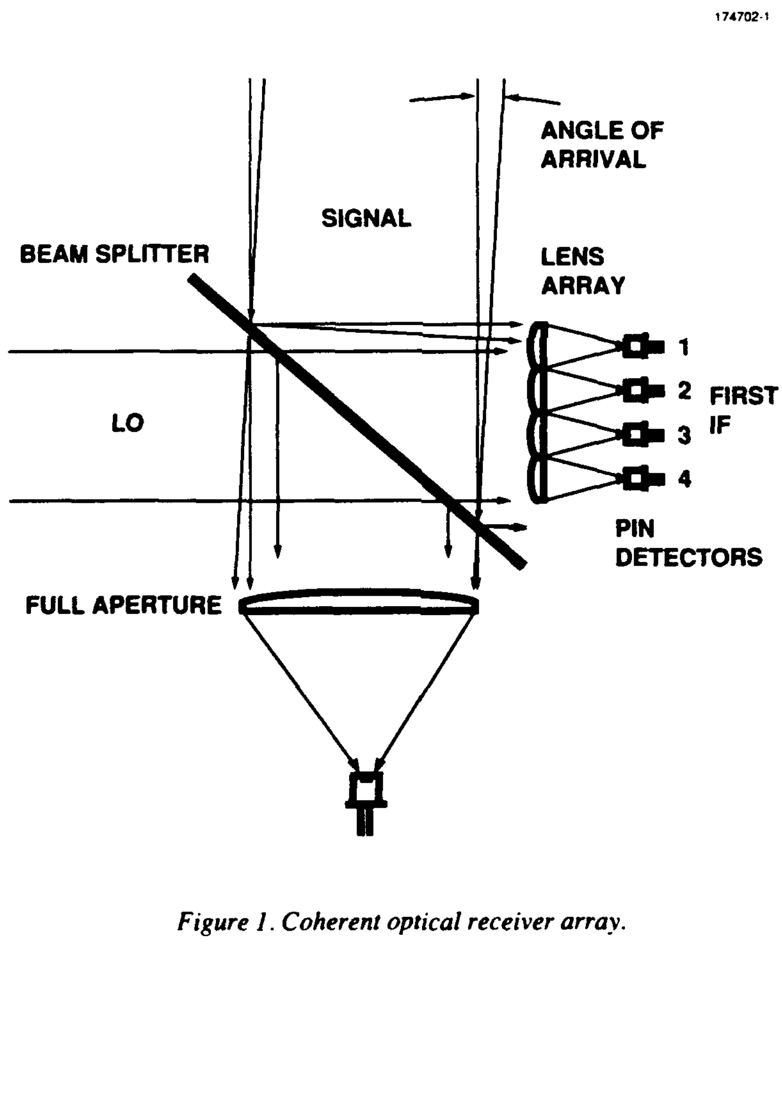

Figure 1. Coherent optical receiver array.

The first IF signals could have different phases due to any combination of signal or LO wavefront tilt or distortion and different optical and RF path delays. To allow coherent summing, the phase of each signal is adjusted by using separate voltage-controlled oscillators (VCOs) to phase lock each second IF signal to the reference channel, subaperture 1 [3]. This subaperture was chosen over one of the central subapertures to stress the system by providing the greatest difference in phase between channel 4 and the reference, as shown in Figure 2. The phase-error signal, which is obtained by correlating the second IF signal with the reference channel, is filtered and then coupled to the VCO to match the second IF phase to the reference phase. To maintain a constant response from the mixer that is used as a phase detector, each input is amplified and hard limited. The loop filter consists of a single integrator that provides a type II PLL. The PLLs each have a natural frequency of 10 kHz and a damping factor of about 0.7.

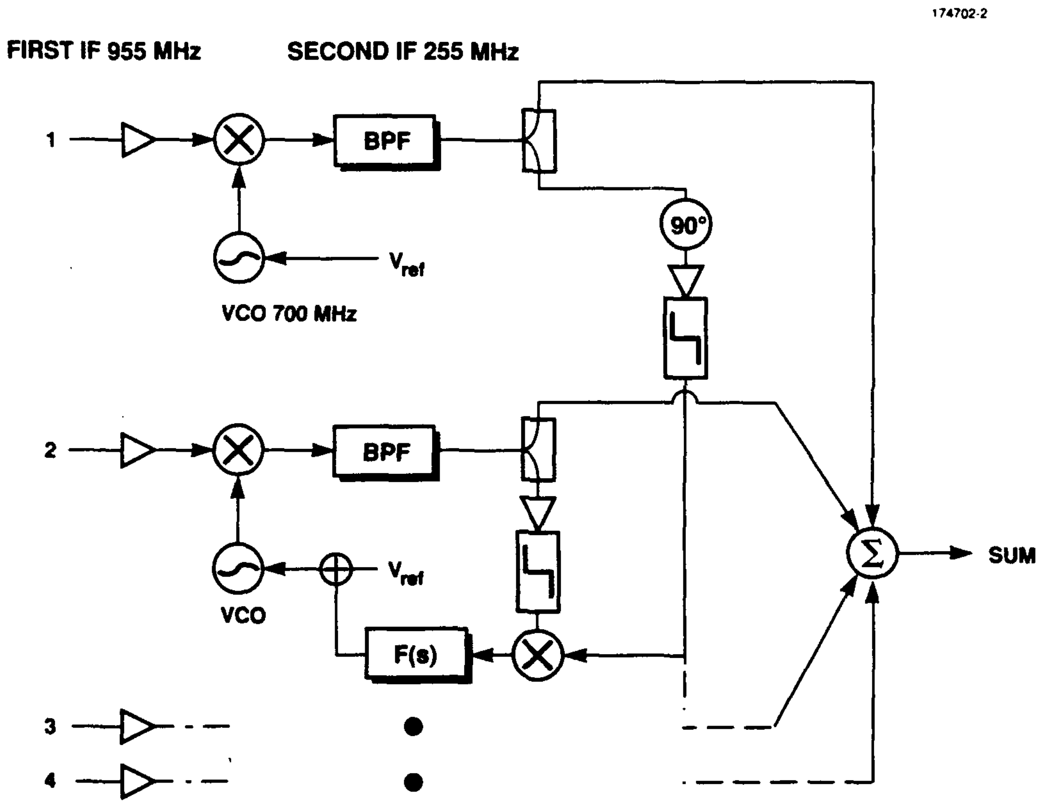

Figure 2. Signal processing for adaptive array.

By locking each channel to a reference channel instead of locking to a reference oscillator, the array is able to adapt even with large linewidth LOs and signal lasers and the array does not require a pilot signal even when the signal laser is modulated. Locking to a reference oscillator would require the use of a pilot signal with a linewidth much smaller than the tracking bandwidth of the PLLs and thus is not practical when using wide linewidth sources. Locking to a reference channel or locking to the sum signal reduces the bandwidth requirement to the tracking of changes in the phase that are due to wavefront tilt or distortion, given that the LO for each receiver is derived from the same source. Locking to the sum signal promises better system operation because of the improved signal-to-noise ratio (SNR) of the sum signal; however, time delays must be considered carefully to avoid offsets in the phase-error signal due to correlation of the channel signal with the component of the sum signal that is from the same channel. Locking to the reference channel was chosen for our initial demonstration because it was easy to implement.

3. RESULTS

The relative SNR of a single subaperture, aperture 1, and the full aperture are shown in Figure 3 along with the $\sin^2(\pi\Theta d/\lambda)/(\pi\Theta d/\lambda)^2$ response predicted for each of these apertures. (The full aperture and aperture 1 responses are normalized to 0 and -6 dB respectively to show the expected increase in SNR.) Under ideal conditions the full aperture has a 6 dB aovantage over the smaller subapertures; however, the subaperture begins to win even for a small misalignment. The motivation for the array design is to obtain the SNR performance of the full aperture over the wider subaperture field-of-view and the reduced wavefront quality requirements of the subapertures. The measured subaperture response is very close to the theory; however, the measured response for the full aperture is significantly broader than the theory predicts. This difference is probably due to distortion of the LO and signal field wavefronts and the fact that each of these optical beams actually had truncated Gaussian intensity profiles instead c ˜ 'he uniform profiles assumed by the theory. It is useful to observe that the smaller apertures are much less sensitive to these conditions than the full aperture.

Assuming equal signal levels and equal independent noise levels in each channel of the array, the maximum SNR for the sum signal is obtained when each channel is in phase allowing the signals to add coherently. For four channels, the resulting signal level should be 12 dB higher and the resulting noise level

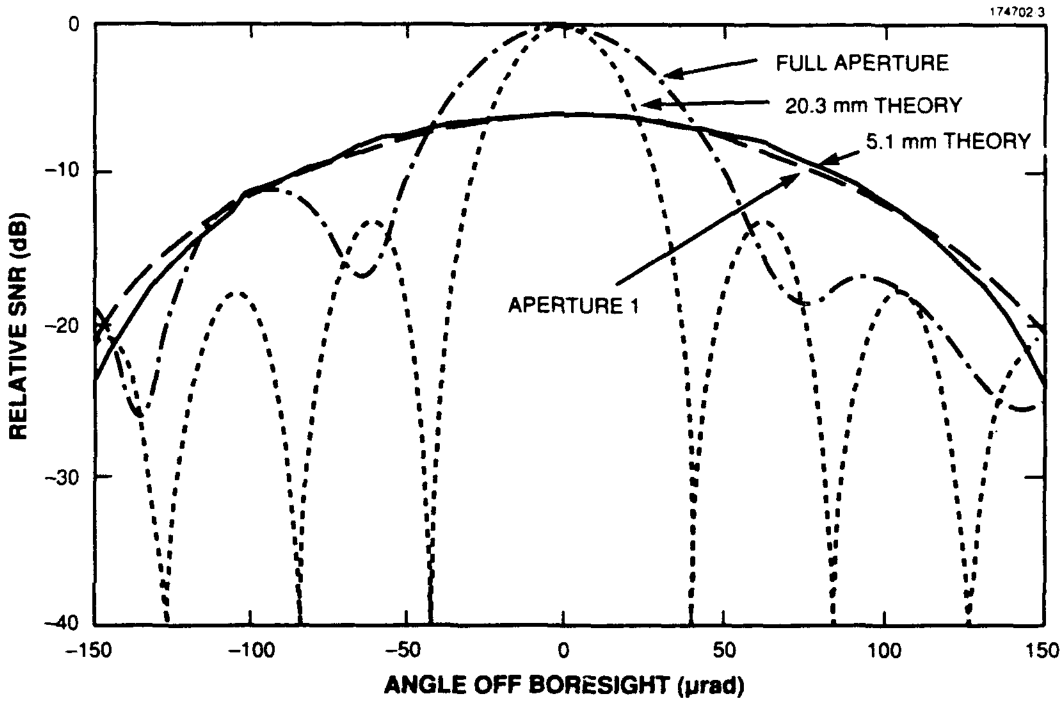

Figure 3. Full and subaperture SNR versus received signal anlge of arrival.

should be 6 dB higher. The performance of the array was evaluated by varying the angle of arrival of the signal beam and measuring the RF signal power from each aperture and from the sum of the signals. The results are shown in Figure 4. The curve labeled coherent sum is the square of the sum of the signal amplitudes and thus represents the best performance possible from the array signal processing. The adapted sum is within 0.6 dB of this level for all angles of arrival of the input signal between the half power points. The aperture-to-aperture variations seen in these results are probably due to distortions in the signal and LO wavefronts and nonuniform intensity profiles. For comparison the array was also operated unadapted by shorting the integrator in the PLL filter. This caused each VCO to operate at a slightly different frequency and the subaperture signals to add incoherently. (The average sum signal power equals the sum of the subaperture signal powers.) The results for this unadapted mode were also very close to the expected levels.

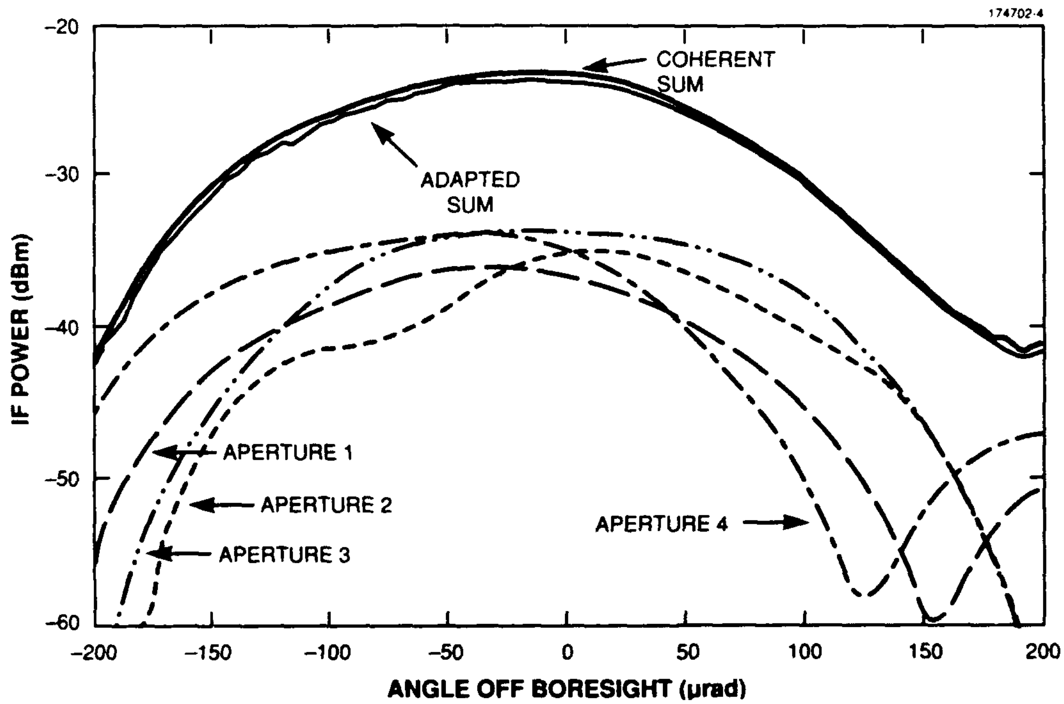

Figure 4. Adapted array signal levels versus received signal angle of arrival.

To illustrate the advantage of the array over an aperture with the same area, the adapted sum and full aperture signals were measured simultaneously as the angle of arrival of the signal beam was varied. The results in Figure 5 show that the array suffers much less from alignment errors than the equivalent single aperture. (The peak levels are arbitrarily normalized.)

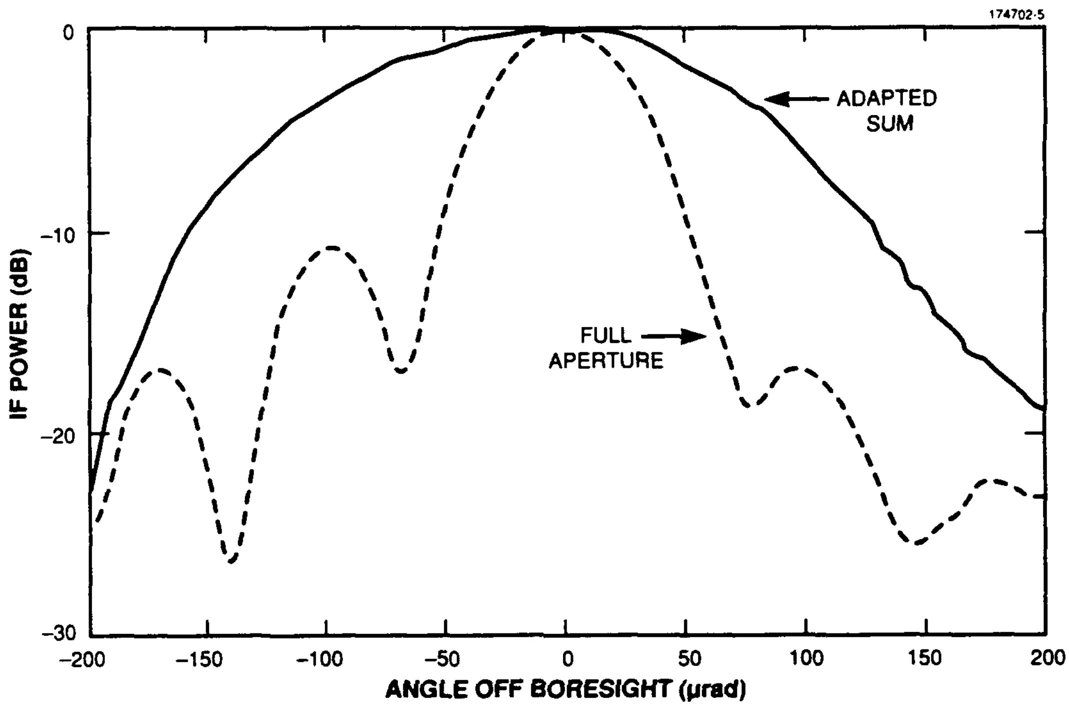

Figure 5. Adapted array signal level and full aperture signal level versus received signal angle of arrival.

4. CONCLUSIONS

An adaptive coherent receiver array has been built using PLLs to match the phases of the subaperture signals to a reference receiver consisting of one of the subapertures. The array has been shown to provide within 0.6 dB of the power expected from perfect coherent summing of the subaperture signals. To our knowledge, this is the first time a phased optical array has been constructed using electronic phase adjustment. The successful demonstration of this array suggests the opportunity for development of coherent optical arrays patterned after any of the numerous RF array configurations.

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L.B. Mercer

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Lincoln Laboratory, MIT
P.O. Box 73
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