Co-phasing a Large Array of Segmented Lasers via Interferometry and Coherent Beam Combination Methods

Eric Mitchell,Micheal Hart

College of Optical Sciences, University of Arizona, Tucson, AZ 85721,USA

ABSTRACT

The Breakthrough Starshot Initiatives aims to launch a nanocraft at 20 percent the speed of light to Proxima Centauri b. The spacecraft will be accelerated with a 1064 nm laser beam of 100 GW propagated from a launch projector of several kilometer diameter. We consider a projector architecture constructed as a dense co-phased array of 2 m telescopes transmitting the light from many thousands of laser power amplifiers slaved to a single maser oscillator (MO). The resulting system is intended to produce a diffraction-limited beam at a distance of 0.3 AU. Implementation of adaptive optics in the segmented beam propagation systems is essential to overcome atmospheric aberration and phase jitter between the lasers. We investigate the use of coherent beam combination and pairwise interferometry methods to measure and correct phase errors between the drive lasers at the projection apertures. Path length differences must be measured and corrected to below $\lambda/20$ to properly phase the sub-apertures. A small portion of light will be sampled from the output of each amplifier and coherently mixed with frequency modulated reference light from the MO, then demodulated to measure the phase error. We then feed the error back to an EOM to correct the phase jitter in closed loop. This method can detect small phase excursions below $\lambda/30$ with relatively low bandwidth requirements ($\sim 10^6$ Hz). Proceeding from the beam transport optics, the light must be expanded through the launch projection apertures where additional co-phasing errors will inevitably be introduced. Piston sensing between segments will be carried out by a separate system looking at light from Proxima Centauri itself seen through coherently combined pairs of sub-apertures spanning the segment gaps. The phase of the interference fringes will be the piston error from the lower lying atmosphere and slowly varying instrumental components.

Keywords: Adaptive optics, co-phased array, segmented lasers

1. INTRODUCTION

Proxima Centauri b is an exoplanet in the Alpha Centauri star system located 4.2 light years from earth. The goal of the Breakthrough Starshot Initiatives is to travel to Proxima Centauri, gather images and data, and send the information back over a human time scale. To accomplish this task, the project aims to accelerate a small spacecraft attached to a lightsail to 20% the speed of light to arrive at Proxima Cen in only 20 years. The spacecraft will be accelerated by a dense co-phased array of lasers slaved to a single master oscillator (MO). The resulting beam will be a $\lambda = 1064$ nm, 100 GW diffraction limited beam at a distance of 0.3 AU. To achieve these specifications, the phased array will be several kilometers in diameter and each sub-aperture laser must remain coherent throughout the 10-minute launch time. This requirement presents a challenge for the beam correction adaptive optics system necessary to overcome atmospheric aberrations. Phase calibration of each laser sub-aperture is necessary for efficient beam combination.

In a MO, power amplifier laser architecture there are many regions where aberrations and phase errors can occur. In the beam transport optics between the MO and sub-aperture outputs, there are two main places where phase errors may arise: optical path length differences in the beam path and phase jitter/drift from the power amplifiers. Proceeding from the projection apertures, additional phase errors will arise from the beam expanding optics and other instrumental components. We adopt a requirement that phase errors must be corrected to

Further author information: (Send correspondence to Eric Mitchell)
Eric Mitchell: E-mail: emitchell1@optics.arizona.edu
Michael Hart: E-mail: mhart@optics.arizona.edu

better than $\lambda/10$ which will yield a Strehl ratio degradation of no more than 0.67.[1,2] Phase errors will also be introduced by atmospheric aberrations; our architecture assumes that those will be measured separately.

In the remainder of this paper, we describe two methods for measuring and correcting the phase error in the large array of coherently combined lasers. Section 2 addresses the issue of minimizing the phase jitter exiting the power amplifier using heterodyne detection to measure the phase excursion and a feedback loop to phase modulators to correct for the errors in closed loop. Section 3 explores a separate system to measure the phase error between the sub-apertures. Methods of phasing an array of coherently combined lasers such as optical phase-locked loops[2] and self-referenced phase locking[3] have proven successful in minimizing phase errors in coherent beam combining systems. Also, conventional phase retrieval algorithms have proven to be a simple and effective method to measure phase errors in sparse aperture telescope imaging systems.[4,5] However, with the sheer size of the array and the requirement of fast and precise measurement of phase error in our application, other solutions may be required to successfully co-phase a laser array of this scale. We investigate the validity of Redundant Spacing Calibration (RSC) to co-phase this large array of lasers.

2. MINIMIZATION OF PHASE JITTER EXITING POWER AMPLIFIERS

Heterodyne detection is an ideal method to measure small phase excursion and optical path length errors with high sensitivity and low bandwidth requirements. There are a few design considerations for this method to achieve the required measurement precision. For this type of detection, it is important for the local oscillator (reference path) power to be much stronger than the signal path to achieve shot noise limited detection. For a shot noise limited system with no misalignment between the LO and the signal fields, the SNR is given by

$$SNR = \frac{\eta P_s}{h\nu B}\,, \tag{1}$$

where η is the detector quantum efficiency, P_s the signal power, ν the optical frequency, h Planck's constant, and B is the detector noise bandwidth. With this type of coherent detection, we can measure milliradians of phase error with only megahertz of bandwidth requirement. Despite the strict alignment requirements, optical heterodyne detection is well suited to this type of application.

Fig. 1 shows the experimental sketch of the phase jitter experiment. The master oscillator is split into three paths: two output and one reference (local oscillator) path. The reference path is frequency shifted by 100 MHz with an AOM and the first order used as the LO. The signal path passes through the laser amplifiers and to the output of the sub-aperture. At the exit of the output, a small sample is reflected back through the system following the amplifiers. When this signal path is mixed with the LO, a 100 MHz beat note is produced and the phase is measured electronically. After measuring the phase drift, the signal is fed back to a phase modulator to correct for the error in closed loop. The phase modulators used in the experiment can correct for the phase of the light at gigahertz speeds, though the speed of the control loop will likely be limited by the post processing of the phase measurement.

3. CO-PHASING THE LASER ARRAY

Fast and precise phase calibration is necessary for many applications such as passive interferometric synthetic aperture imaging systems. A method known as redundant spacing calibration (RSC) has proved to be a useful solution for phase error measurements in an imaging systems.[6,7] RSC is a method based on a principle derived from segmented telescope arrays. Passive interferometric array optimization is based on manipulating the baseline distances between apertures to achieve optimal sampling in the Fourier domain. Significant research has been conducted regarding optimum array configurations.[8–10] Phase calibration of a telescope array is an important step for image reconstruction and, in this work, for efficient combination of lasers.

For a segmented N aperture system,the number of baselines is given by

$$p = \frac{N(N-1)}{2} \tag{2}$$

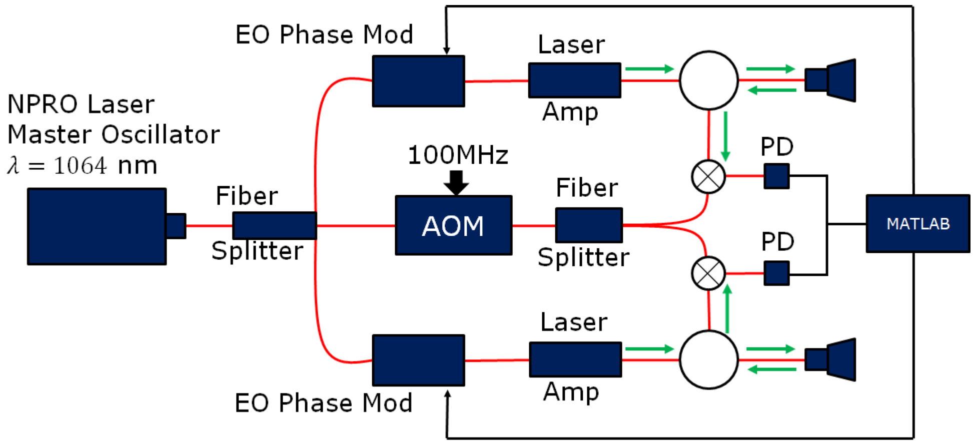


Figure 1. Phase jitter measurement and correction experiement. The LO is frequency shifted by 100 MHz. The MATLAB processing may be replaced by an FPGA depending on the feedback loop requirements.

Consider the baseline pair (i, j); the phase of mutual coherence for this baseline is

$$m_{ij} = \phi_{ij} + (e_i + e_j) \tag{3}$$

where ϕ_{ij} is the "true" baseline phase and e_i, e_j are the phase errors for apertures i and j,respectively. The baseline phase can be combined in matrix form as

$$\mathbf{M}_{p\times 1} = \mathbf{A}_{p\times(p+N)}\mathbf{U}_{(p+N)\times 1} \tag{4}$$

In this equation, $\mathbf{M}$ is a vector of p measurements, $\mathbf{A}$ is a vector operator which maps the baseline phase to the errors, and $\mathbf{U}$ contains the true baseline phases and phase errors for each aperture. From Equation 4, it is clear that there are $(p + N)$ unknown values and only p linear equations. Therefore, $\mathbf{A}$ is rank deficient and will not converge to a unique solution for the phase errors.[10]

Specifically designed geometric configurations of apertures based on the principle of RSC have enough redundancies built in to calibrate the phase errors of the individual laser apertures. If two pairs of sub-apertures have the same baseline vector, they will measure the same Fourier component. Therefore, if the complex visibilities differ, this difference can only be due to mechanical error and atmospheric aberrations.[6]

The goal of RSC is to provide enough redundancies in the baseline to have a sufficient number of linear relationships to solve for $\mathbf{U}$. Additionally, for a 1D array of apertures there are two free parameters (for a 2D array there are three): one true phase of any non-redundant baseline and one aperture phase error.[7] With proper RSC geometry and the free parameters in the system, the above equation can be solved to produce a unique solution for the phase error.

Fig. 2 gives an example of a simple algorithm to determine a RSC solution for a 1D linear array of laser apertures. For this simulation, r is the number of independent redundant baselines. Equation 4 suggests there is a requirement for r to obtain a unique minimum-norm least square solution.

- **Case1**: $r < N - 2 \implies Nullity(\mathbf{A}) \neq 0$ (no unique solution)
- **Case2**: $r = N - 2 \implies \mathbf{A}_{(p+r+2)\times(p+N)} = \mathbf{A}_{(p+N)\times(p+N)}$
- **Case3**: $r > N - 2 \implies$ Solution found by applying singular value decomposition to $\mathbf{A}$[10]

The array geometry must satisfy two conditions to determine a unique solution for the phase errors: 1) Each baseline value can only have a maximum of two redundancies (independent redundant baselines), 2) the number of independent redundant baselines must be greater than or equal to $N-2$. Fig. 3 shows each baseline with the number of redundancies found in the solution. The solution has 6 apertures to solve for the phase errors. Clearly there are 5 independent redundancies in the aperture array. So the solution will fall under case 3 described above and Equation 4 can be solved by determining the pseudo-inverse of $\mathbf{A}$ and solving for $\mathbf{U}$. This equation also points out an important advantage of RSC: the matrix $\mathbf{A}$ is only dependent on the geometric configuration of the apertures under test. Therefore, matrix $\mathbf{A}$ can be precomputed making phase correction fast and potentially real-time.

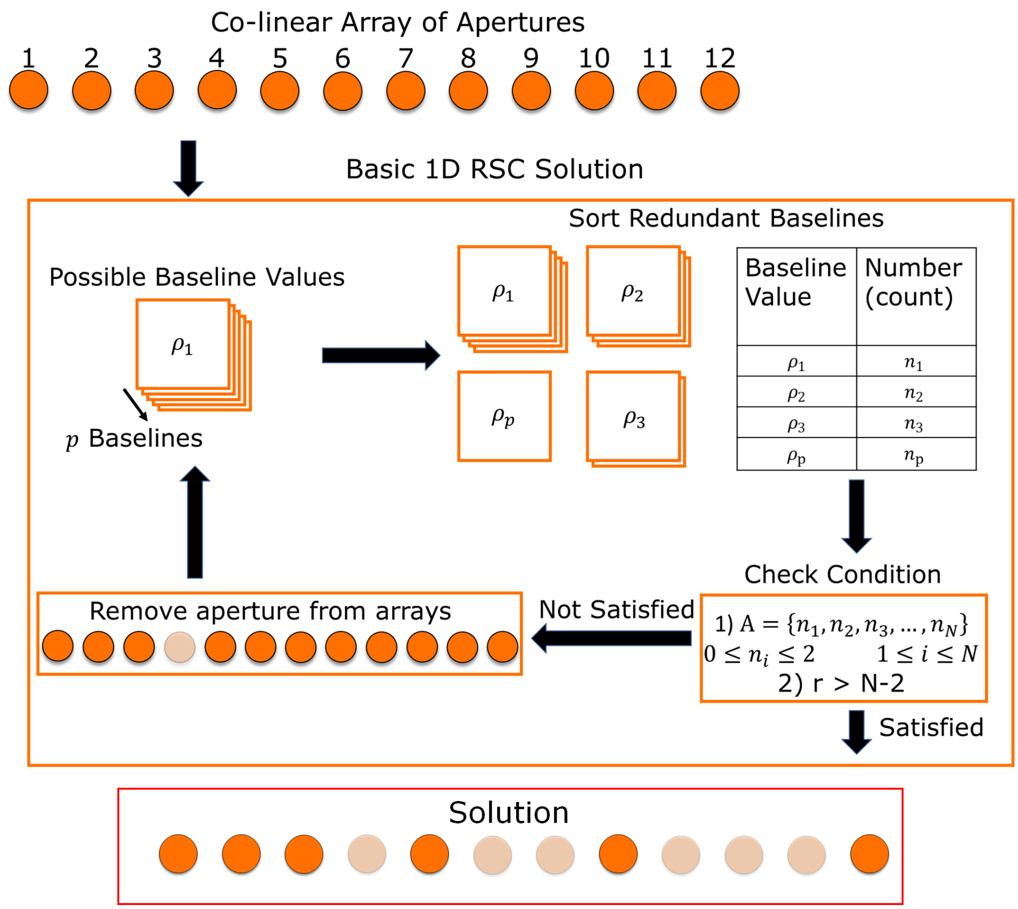
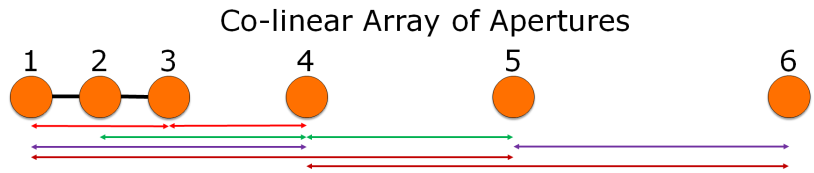


Figure 2. Example RSC algorithm. The circles are the laser launch sub-aperture and the transparent circles are the apertures not considered in the final solution to satisfy the redundancy requirements. The process began with 12 apertures and the solution only left 6 apertures to be co-phased.



Baseline	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
Redundancy	2	2	2	2	1	1	2	0	1	1	1
Color											

Figure 3. Example N=6 RSC geometry. The apertures are spaced by a half unit for simplicity.

4. CONCLUSION

We explored the ideas of coherent detection and redundant spacing calibration to measure the phase errors in a large array of lasers for the Breakthrough Starshot Initiatives. Heterodyne detection is an attractive method for measuring phase jitter exiting the power amplifiers because of its high sensitivity and bandwidth requirements. Currently, we are constructing a benchtop version with multiple apertures to test this method. Further work will seek to understand how this technique will handle a large number of apertures and expected phase excursions of the reference beam over a few kilometers. The method of RSC to measure the phase error between the apertures is advantageous because it could allow for real time measurement of phase error. Since the method must satisfy the redundancy requires outlined in section 3 it cannot be applied directly to the highly redundant and nearly filled aperture of the Starshot launch projector: only a limited number of apertures can be phased together at a time. Ongoing work is looking at grouping interleaved subsets of the projector elements into non-redundant arrays that collectively account for all the elements. A hierarchical approach in which non-redundant arrays of arrays are defined shows promise for tying the subsets together and establishing the phase relationships between them.

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REFERENCES

[1] Augst, S. J., Fan, T. Y., and Sanchez, A., "Coherent beam combining and phase noise measurements of ytterbium fiber amplifiers," *Opt. Lett.* **29**, 474–476 (Mar 2004).

[2] Liang, W., Satyan, N., Aflatouni, F., Yariv, A., Kewitsch, A., Rakuljic, G., and Hashemi, H., "Coherent beam combining with multilevel optical phase-locked loops," *J. Opt. Soc. Am. B* **24**, 2930–2939 (Dec 2007).

[3] T. M. Shay, Vincent Benham, J. S. B. W. F. G. M. A. C. A. D. S. J. T. B. D. P. R. B., "Self-referenced locking of optical coherence by single-detector electronic-frequency tagging," (2006).

[4] Miller, N. J., Dierking, M. P., and Duncan, B. D., "Optical sparse aperture imaging," *Appl. Opt.* **46**, 5933–5943 (Aug 2007).

[5] Baron, F., Mocoeur, I., Cassaing, F., and Mugnier, L. M., "Unambiguous phase retrieval as a cophasing sensor for phased array telescopes," *J. Opt. Soc. Am. A* **25**, 1000–1015 (May 2008).

[6] Lannes, A. and Éric Anterrieu, "Redundant spacing calibration: phase restoration methods," *J. Opt. Soc. Am. A* **16**, 2866–2879 (Dec 1999).

[7] Blanchard, P. M., Greenaway, A. H., Harvey, A. R., and Webster, K., "Coherent optical beam forming with passive millimeter-wave arrays," *Journal of Lightwave Technology* **17**, 418–425 (March 1999).

[8] Iouri Tcherniavski, M. K., "Optimization of the optical sparse array configuration," *Optical Engineering* **44**(10), 1 – 10 – 10 (2005).

[9] Tcherniavski, I. and Kahrizi, M., "Optimization of design and operating parameters of a space-based optical-electronic system with a distributed aperture," *Appl. Opt.* **47**, 6159–6176 (Nov 2008).

[10] He, Y., Jiang, Y., Liu, L., and Wang, C., "Passive interferometric array optimization based on redundant spacing calibration," *Opt. Express* **17**, 21598–21607 (Nov 2009).