Photon Phase Shift Imaging Research on Frequency Domain Diffuse Optic Tomography

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Research Article

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Photon Phase Shift Imaging Research on Frequency Domain Diffuse Optic Tomography

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Abstract. Diffuse optic imaging is an important biomedical optic research tool. Diffuse optic tomography (DOT) modality needs progressive philosophical approaches for scientific contribution. Technological developments and philosophical approaches should both go forward. Phase-shift based frequency domain (FD) diffuse optical tomography (FDDOT) method was well established in the literature. The instruments were tested for brain neurofunctional imaging. A mixture of AC laser intensity and phase data were used at these works. According to those works; deep volume resolution was improved by only using phase data. Because phase data is only related to the photon mean free path in imaging tissue media. Besides this advantage, laser intensity data is also affected by noisy background light and electrical artifacts. Another most important advantage of only using phase data can be explained as time-resolved temporal change can be directly related to phase shift of modulated frequency source. At this work, the frequency domain (FD) DOT imaging method which uses phase shift data were used for simulation phantom. Laser source-driven forward model problem weight matrix simulation data was given to the simple pseudo-inverse-based inverse problem solution algorithm for one inclusion example. The inclusion image was reconstructed and demonstrated successfully. Forward model problem weight functions inside the tissue simulation media were calculated and used based on the phase shifts at the same core modulation frequency. 100 MHz modulation frequency was selected due to its FDDOT standard. 13 sources and 13 detectors were placed on the back-reflected imaging surface. 40 x, y, z cartesian coordinate grid elements were used in the image reconstruction algorithm. Photon absorption coefficient: $\mu_a = 0.1$ cm^{-1}, and scattering coefficient: $\mu_s = 100$ cm^{-1} values were set for background simulation phantom. One inclusion object was embedded inside the imaging tissue simulation phantom background. x, y, z cartesian coordinate grid sizes were selected for 100 μm for each direction. Photon phase shift fluencies were added to the forward model problem. The forward model problem was built according to the frequency domain photon migration diffusion approximation. Forward model problem photon fluencies were calculated according to the diffusion equation approximation. The simple pseudoinverse mathematical inverse problem solution algorithm was applied to test the results. The embedded inclusion object was reconstructed successfully with the high-resolution image quality. In general, DOT techniques suffer for the low image quality, but in this work, the high-quality image was reconstructed and demonstrated. The philosophical approach has future promising DOT imaging capability. The phase shift version of the FDDOT modality has an important advantage for future purpose.

Keywords: Frequency domain (FD) diffuse optic tomography (DOT), photon phase shift imaging (PPSI).

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1. INTRODUCTION

Practical diagnostic techniques are essential to test and evaluate blood contents quickly. For this purpose, in this work existing improved frequency domain (FD) diffuse optical tomography (FDDOT) imaging technique was invoked to build a philosophical method by using biomedical photonic tools. In general terms, DOT techniques suffer from low spatial resolution and background noise. But in the past 2 years, researchers associated successful FDDOT techniques which gets benefit from phase shift only data. At the beginning of the diffuse optic imaging (DOI) era 3 decades ago, phase-shift-based FDDOT works were well established[1]. The successful biomedical optic imaging devices were developed and tested[2, 3]. Finally, the researchers depicted better deep tissue spatial resolution results[4,5] by using FDDOT. They improved the image quality by using a mixture of phase and AC intensity data of the FDDOT system. Phase data is independent of the intensity data, it can only be related to the photon mean free paths. On the contrary, AC laser intensity data is affected by noisy light background and electrical artifacts. More importantly, time-resolved temporal change can be directly correlated to the phase shift of modulation frequency. FDDOT works were completed by the researchers for different clinics with various imagers such as by placing source and detectors on the back-reflected, transmission, or ring geometry. The review of these works was compiled in the literature[6]. FDDOT techniques for functional brain imaging were also presented comprehensively[7]. Basic instrumentational perspective and device developing methodology were also mentioned and tested for breast imaging at frequency domain[8]. Recent developments and progressive efforts were also summarized[9]. Frequency domain research was evaluated[10]. For ring imaging geometry, physical formula extraction from radiative transfer equation (RTE) and its usage in the FDDOT system was given[11]. At this work, FDDOT imaging methodology with the help of phase shift laser source driven forward model problem weight matrix simulation data was given to the simple pseudo-inverse based inverse problem solution algorithm for a simple inclusion example. The wavelength of the laser source was chosen according to the literature search[12]. 500

nm laser wavelength was chosen for a possible microbial investigation case. Different phase shifts related to the microbial particle diameter size were applied and reconstructed images were compared and presented to the readers. Forward model problem photon weight functions inside the imaging tissue simulation media were calculated and used with the phase shifts at the same modulation core frequency. 100 MHz modulation frequency was selected. 13 sources and 13 detectors were placed on the back-reflected imaging surface. 40 x, y, z grid elements were used for image reconstruction purposes. Photon absorption coefficient: $\mu_a = 0.1$ cm^{-1}, and scattering coefficient: $\mu_s = 100$ cm^{-1}. One inclusion object was embedded inside the imaging tissue simulation phantom. Cartesian grid coordinate x, y, z sizes were selected as 100 μm for each direction. Over the traditional image reconstruction algorithms, extra photon phase shift fluencies were added to the forward problem. The forward model problem was built according to the frequency domain photon migration diffusion approach. Photon fluencies were calculated in the forward model. The simple pseudoinverse mathematical inverse problem solution algorithm was applied for the solution. The image of the embedded inclusion object was reconstructed successfully with the high-resolution quality.

2. METHOD

In general, a 500 nm laser wavelength source is used to detect microbial instances. For this purpose, it is assumed to use 500 nm laser wavelength, and pre-calculations were done according to the center laser wavelength. The specific microbial instance has a 100-120 nm diameter size. It could be presumed the size of microbial instance is around 100 nm. One complete laser wave overlaps 5 microbial instances. 500 ÷ 100 = 5 phase-shift steps would be thought for minimum full interaction. Let us assume tissue refraction index n = 1.37. According to the $c = \lambda \times f \Rightarrow f = c \div \lambda$, $f = 3 \times 10^8$ m ÷ 1.37 ÷ (500×10^{-9}) m = 4.37×10^{14} Hz ==> We need to have almost $t = 1 \div (4.37 \times 10^{14}) = 2.28$ femtoseconds (fs) full-wave photonic resolution. In one

full wave, we need 5 phase-shift steps, we have 2.28 fs ÷ 5 = 0.456 femtoseconds (fs) resolution steps. If we have frequency modulated continuous waves (EFMCW) step up and down by 5 Hz steps, then time differences between 2 EFMCW waves become $1\div(100\times10^6)$ - $1\div(100000005)$ = 0.5 femtoseconds (fs). 100 sequential phases were sent from source positions with 5 Hz phase-shift which corresponds to the 5 fs time delay at 100 MHz core frequency.

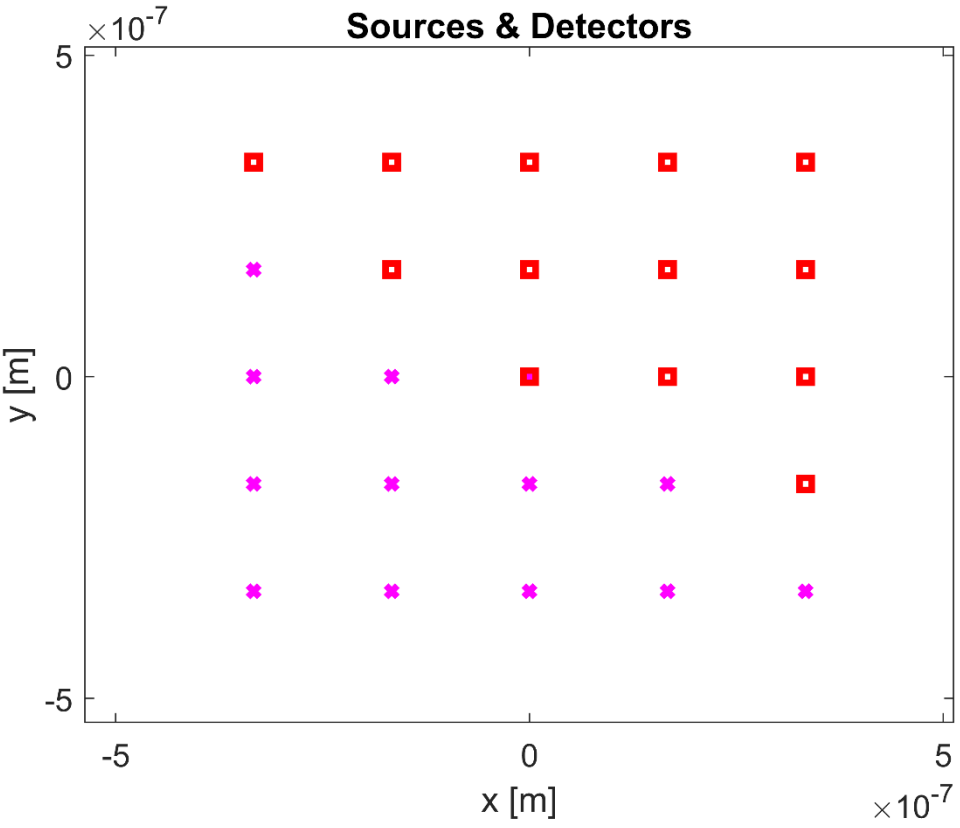

Figure 1. Source and detector placements. Sources are magenta, and detectors are red.

N_s=13 sources and Nd=13 detectors were placed based on the back-reflected imaging geometry structure which was demonstrated in Figure 1. Sources are magenta, and detectors are red. Figure 1 has a top-view appearance for sources and detectors. Forward model problem weight matrix functions were calculated according to the frequency domain extraction of diffusion approximation radiative transport equation[13].

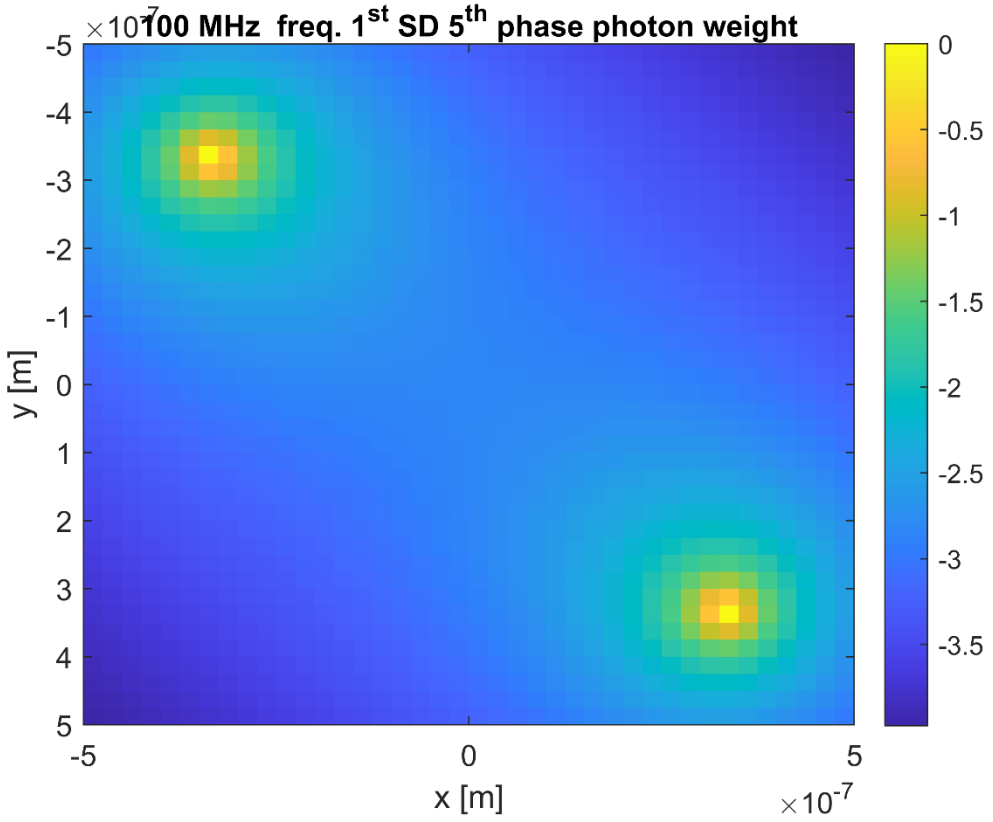

Figure 2. 1st source-detector (SD) match 5th phase.

First source-detector (SD) match, 5th phase frequency-domain photon fluence weight functions distribution was demonstrated at the top-view in Figure 2. Source and detector positions have hotspots where their positions can be realized as yellow colors. Forward model problem was generated between all SD couplings with all sequential phase shifts. Figure 1 depicts only one SD match 5th phase photon fluencies which was seen from the top view. Forward model problem weight matrix has 16900 × 64000 dimensions. The total SD match is 13 sources × 13 detectors = 169. Each SD match has 100 sequential phase shift data. The total SD match and phase shift data together are 169 × 100 = 16900. Voxel dimension is 40 × 40 × 40 = 64000. The weight matrix represents the forward model problem weight functions distribution.

3. RESULTS

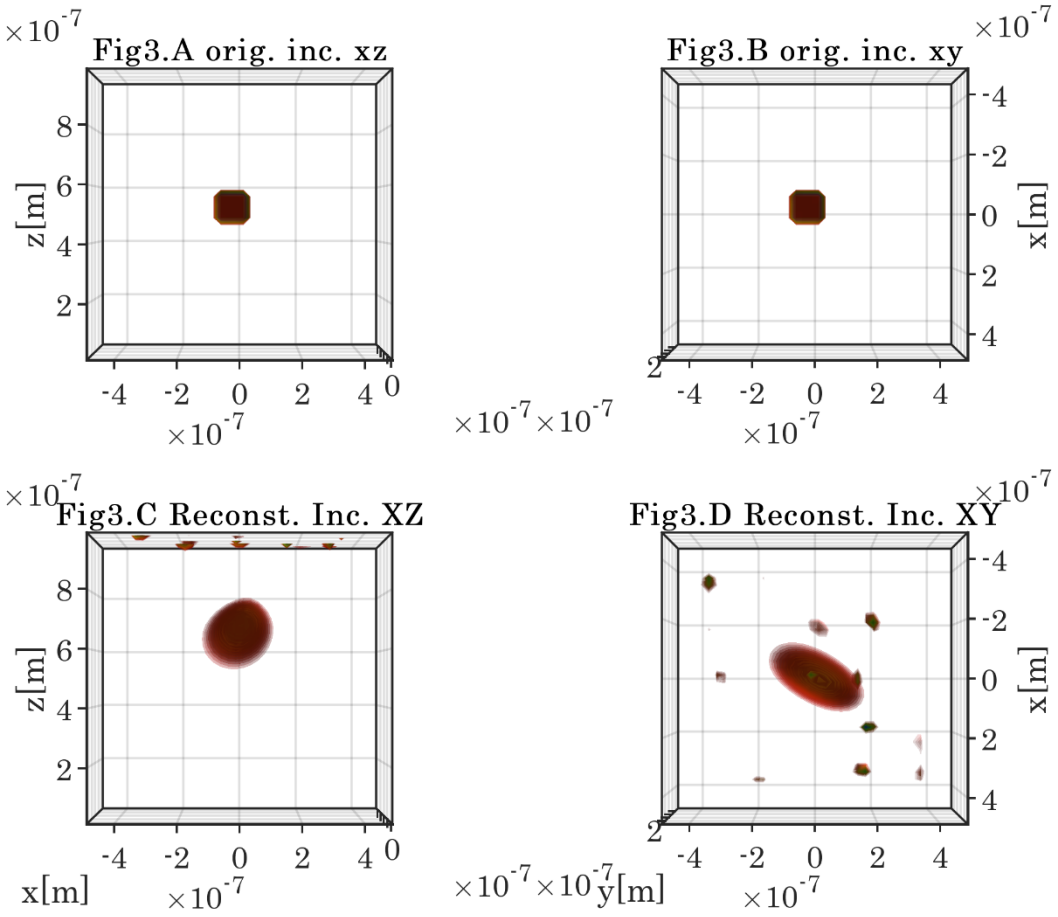

Figure 3. Original and reconstructed inclusion images.

In Figure 3.A and Figure 3.B, the original embedded object can be seen. In Figure 3.C and Figure 3.D reconstructed image can be seen clearly. The original inclusion object has 100 nm size on x, y, and z directions. Depth resolution can be evaluated from the view of Figure 3.C. The top view can be seen from Figure 3.D. A simple pseudo-inverse problem solution algorithm was applied to reconstruct the inclusion object image.

4. DISCUSSION

In this work, a well-known FDDOT imaging modality with only phase-shift simulation data was studied to reconstruct the inclusion image object. According to this method, using only the modulation signal phase is the key factor. Since the DOT methodologies easily suffer from background light and electrical artifacts, AC and DC magnitude investigations were ignored, and only phase data was used and tested for better time-resolved temporal image quality and depth resolution. 100 sequential phases were used for 100 MHz core modulation frequency. It was seen that phase shift methodology would be easily applied to future FDDOT devices. Technological developments are necessary to design and implement the micrometric frequency domain back-reflected laser tomography devices. In the possible future work scenario, photonic integrated circuits (PIC) design would be gathered with the traditional analog electronic VLSI design for high-resolution temporal time-resolved phase shifts. Time resolved imaging approach is equivalent to the frequency domain phase shift method. New easy-to apply time resolved imaging methodologies are necessary for DOT imaging methodology. For this reason, time resolved equivalency of the DOT modality was presented to the authors for high image resolution for future works.

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Competing Interest

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Financial competing interests:

• In the past five years the author has not received reimbursements, fees, funding, or salary from any organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future. The author works as Associate Prof. Dr. & Researcher at university that are not financing this manuscript (including the article-processing charge).

The author has not held any stocks or shares in an organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future.

• The author does not hold, or he is not currently applying for any patents relating to the content of the manuscript. The author has not received reimbursements, fees, funding, or salary from an organization that holds or has applied for patents relating to the content of the manuscript.

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Corresponding Author is **Huseyin Ozgur Kazanci (M'75)** received his B.S. degree in Electronics & Telecommunication Engineering, Microelectronics major from Istanbul Technical University (ITU), Istanbul, Turkey in 1997, and his M.S. degree in Biophysics from Akdeniz University, Antalya, Turkey, in 2009, and his Ph.D. degree in Biophysics from Akdeniz University, Antalya, Turkey, in 2014. From 2006 to 2014, he was a Lecturer in the Akdeniz University, Antalya, Turkey. From 2014 to 2018 April 19th, he was Assistant Professor Dr. Faculty of Engineering, Department of Biomedical Engineering in the Akdeniz University, Antalya, Turkey. He has been Associate Prof. Dr. since 2018 April 19. He is active inventor, designer, and implementer in the field of photomedicine for more than 10 years. His research work includes novel continuous wave diffuse optical imaging (CWDOI) methodologies for biomedical optic imaging research and clinical care, Electronics hardware, and software implementation for diffuse optical tomography (DOT) systems. He developed a CWDOT system for diagnosis of breast cancer, which is used in Akdeniz University Medical School right. He was also visiting researcher in graduate school of electronics, Nagoya, Japan, since 2019 July 1st. He designed and implemented Radio Frequency (RF) based non-invasive glucose measurement integrated circuit (IC) chip, at the TSMC 65 nanometer (nm) technology. He designed and implemented 3-dimensional (3D) Calcium imaging integrated circuit (IC) which he developed at the 22 nm TSMC ULL technology node which has cross-coupled harmonic LCVCO driven with spiral inductances and injection locked frequency divider (ILFD) circuits at the 3x3x2 xyz grid dimensions.

Figure Caption List

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Figure 2. 1st source-detector (SD) match 5th phase.

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Figures

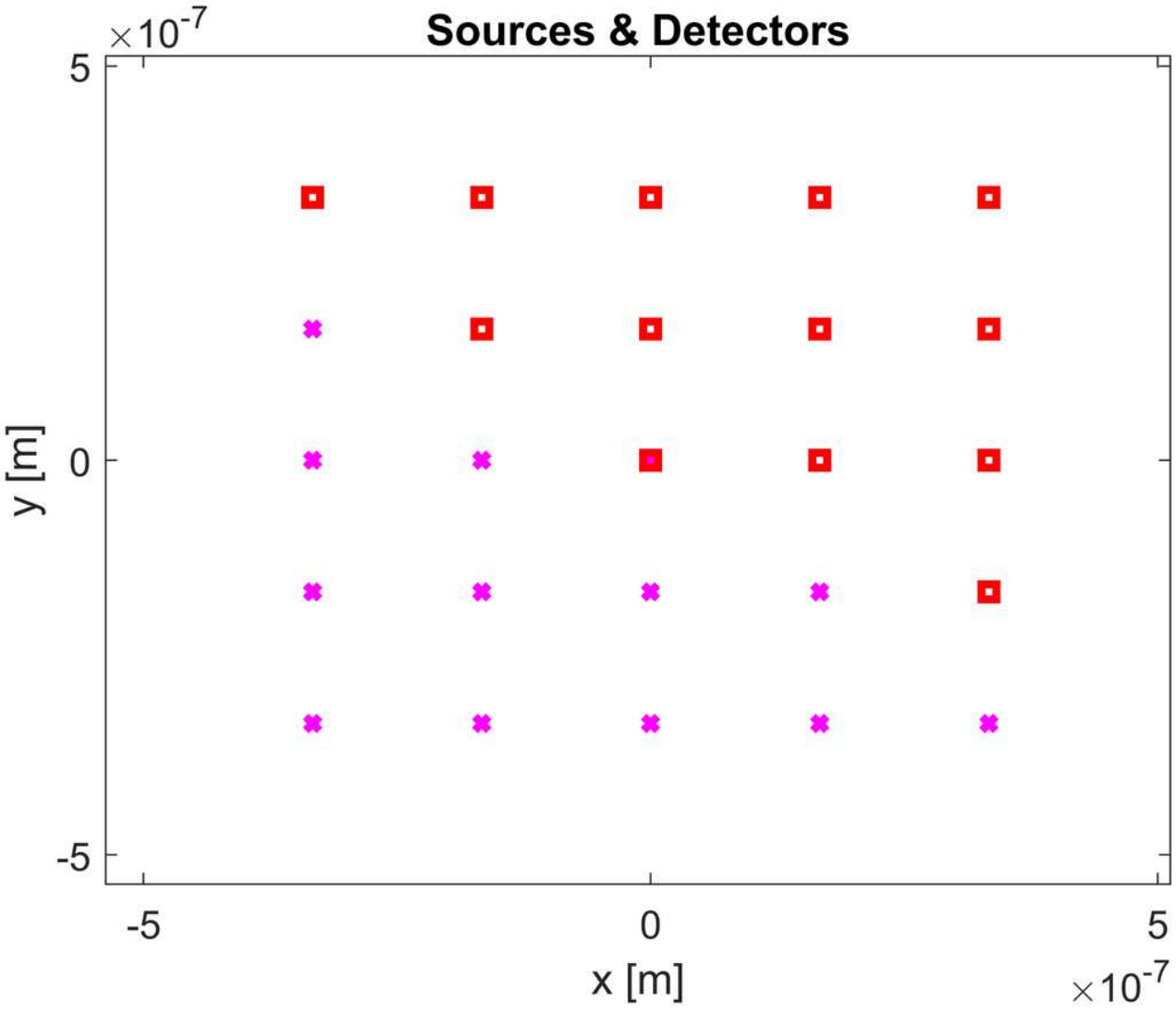

Figure 1

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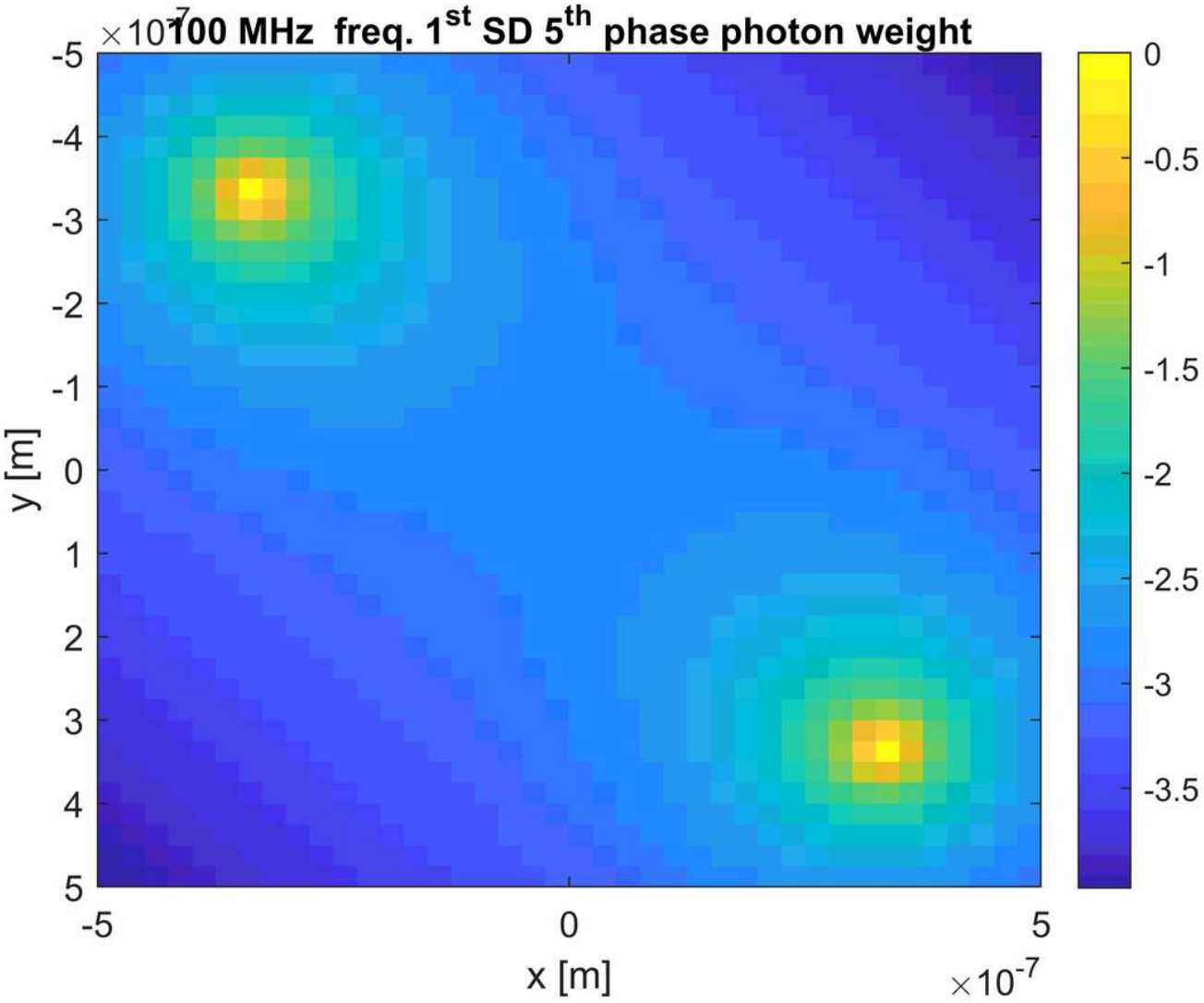
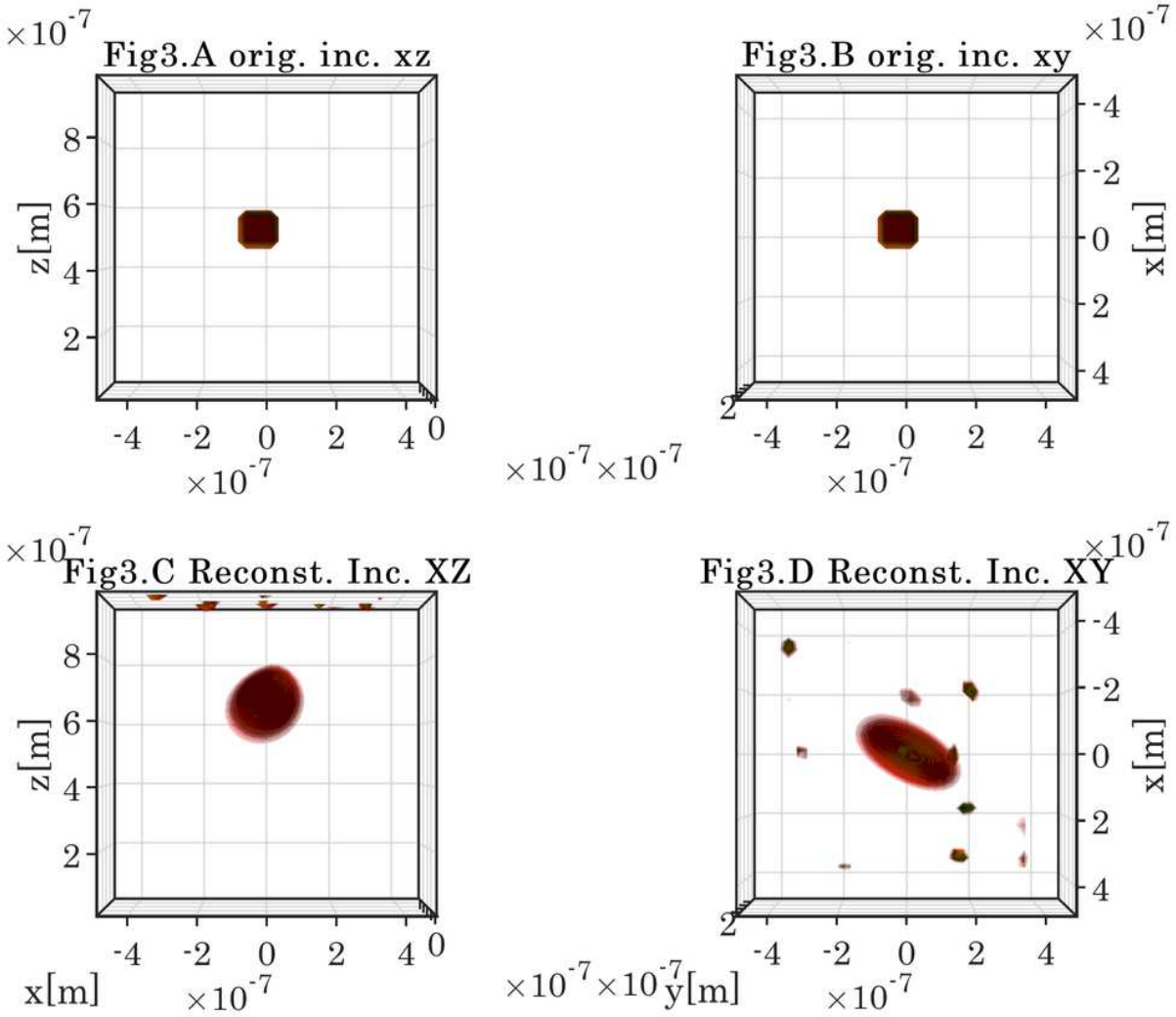


Figure 2

1st source-detector (SD) match 5th phase.



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