

Distributed Array Transmitter Spatial Coherence in Active Incoherent Millimeter-Wave Imaging

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Abstract—We present measurements and analysis of the transmit pattern spatial coherence in active incoherent millimeter-wave imaging systems. Incoherent microwave and millimeter-wave imaging systems have recently attracted research interest due to their ability to generate imagery with reduced hardware requirements compared to coherent systems like phased arrays. Unlike traditional coherent systems and computational imaging where the knowledge of transmit radiation is very important, a newly-developed active incoherent millimeter-wave imaging does not require explicit knowledge of the transmit waveform, provided that the spatial coherence between points in the scene is sufficiently low. In this paper, we introduce a simple measurement to quantify the spatial coherence of waveform impinging on the scene. We present the basic theory and experimental results of the transmission of two noise transmitters.

I. INTRODUCTION

The ability to experimentally measure the coherence of the transmitter illumination in an imaging technique can be a very powerful tool. For example, in computational and compressive imaging techniques sufficient independence must exist between measurement modes so that a norm minimization or matrix inversion problem can be solved [1], [2]. Inverse problems in imaging need such constraints to ensure that the recursive computation of the inverse or pseudo-inverse can succeed. A recently-developed millimeter-wave imaging technique also uses the transmission of incoherent signals and a sparse receiving array [3], [4]. For this technique, exact knowledge of the transmitted signal is not required for image reconstruction, however for a successful image reconstruction the radiation impinging on the scene must be spatio-temporally incoherent. Since it is the incoherence of the emitted signal that is important and not the actual form of the radiation pattern, simplified measurements can be implemented. Although interferometric imaging is not new, it was previously used only in passive systems detecting thermal radiation from celestial sources and the human body, however due to the low power of such signals, passive imagers requires extremely high system gains and bandwidths [5]. By illuminating the scene with incoherent radiation, this limitation is alleviated, and the overall system design becomes simpler and more cost-efficient [3]. No beam scanning or array rotation is needed [6].

When designing an incoherent imaging system, the need for an experimental measurement to determine if each spatial point is sufficiently independent with each other is important. In this paper, we demonstrate an experimental mea-

surement to identify the correlation in the transmitted signal by building on research in the field of optics [7]. While we focus on active interferometric millimeter-wave imaging, the experimental measurement can be applied in any incoherent microwave/millimeter-wave imaging technique [8] and potentially other inverse imaging problems. In particular, incoherent imaging using non-cooperative sources has recently been demonstrated [9], for which the proposed measurement could be used to identify suitable non-cooperative signals.

II. NOISE ILLUMINATION AND INCOHERENCE

Consider three incoherent noise transmitters residing on the $x-y$ plane, where the i^{th} transmitter resides at $(x_i, y_i, 0)$. We consider the superposition of the transmitted signals at a point Q on the object. For the interferometric image reconstruction to succeed each spatial point response needs to be statistically independent from the other. The three independent noise sources are illuminating the point Q from different distances, however the combination of distances r_1 , r_2 , and r_3 is not necessarily unique, since three spheres whose center is at each transmitter can have up to two intersecting points in the three dimensional space. A simple solution to the problem when all three transmitters are coplanar is to conveniently choose the coordinate frame such as $(x_1, y_1, 0)=(0, 0, 0)$, $(x_2, y_2, 0)=(\alpha, 0, 0)$ and $(x_3, y_3, 0)=(\beta, \gamma, 0)$, where α, β, γ are variables that describe transmitter locations. The equations for the three spheres are

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = r_i^2 \quad (1)$$

and their intersecting points (when they exist) can be found through

$$(x, y, z)^T = \left(\frac{r_1^2 - r_2^2 + \alpha^2}{2\alpha}, \frac{r_1^2 - r_3^2 + \beta^2 + \gamma^2 - 2\beta x}{2\gamma}, \pm \sqrt{r_1^2 - x^2 - y^2} \right). \quad (2)$$

The points that will have exactly the same superposition will have the same x and y coordinates, but opposite z coordinate. This is not unexpected, since the problem has symmetry about the $x-y$ plane. These two points will have exactly the same response if the antennas were isotropic, however we can easily assume that directional antennas are used so the solution of the problem for $z < 0$ can be ignored. However, although

there are no other points for $z > 0$ that have exactly the same contributions for the three transmitters, bandwidth and integration time samples in an actual imaging system are not infinite, so spatial points closely together in space will have similar responses. A useful metric to describe how similar the illumination of two points 1 and 2 are is the complex degree of coherence, given by

$$\Gamma_{12}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T E_1(t) E_2^*(t - \tau) dt \quad (3)$$

Usually $\Gamma_{12}(\tau)$ is normalized such as $0 \leq \Gamma_{12}(\tau) \leq 1$, and when trying to characterize spatial coherence between two points 1 and 2 at the same time instance, we use $\Gamma_{12}(0)$.

Measurements of spatial coherence are common in optical physics [10], where partially coherent systems and illuminations are very widely used. This is not the case for microwave and millimeter-wave systems where most of the imaging techniques until recently require some sort of coherent illumination and knowledge of the transmit radiation pattern.

III. EXPERIMENTAL MEASUREMENTS

To evaluate the coherence of the emitted signals at two points in space, we implemented an interferometric correlation receiver, as shown in Fig. 1. Two incoherent transmitters generated noise signals at 37 GHz, which were captured with two receivers at various baseline separations. The two noise signals were generated with an arbitrary waveform generator (AWG) by using multi-tone signals with random phase overlapping over a 0.1-500 MHz bandwidth. The two noise signals were upconverted at 37 GHz using two GaAs MMIC I/Q upconverters and afterwards amplified using two Analog Devices HMC7229LS6 power amplifiers. For the receivers, the signal was amplified by two 20 dB gain Analog Devices HMC1040LP3CE low-noise amplifier (LNAs) and afterwards downconverted to baseband using a 37-44 GHz GaAs MMIC I/Q downconverter. Both for transmitters and receivers we used 15 dBi 3-D printed horn antennas. The baseband response was captured using a 16-channel ATS9416 14 bit, 100 MS/s AlazarTech waveform digitizer. The integration time was 5 ms. The two transmitters were on the same vertical level but separated by a horizontal baseline of 30 cm. The receivers' baseline was 1.8 m away from the transmitters' baseline. The receivers were moved in different horizontal spacing from 3 to 30 cm in 3 cm increments. Although the measurements took place in the near field, because of the transmitter separation, they show a realistic scenario because in many indoor places the far field region can be outside the dimensions of a room.

The measurement results can be seen in Fig. 2. The system measured a mutual coherence of approximately $\Gamma_{12}(0) = 0.08$ to 0.3 over the baseline. While this is not perfect incoherence ($\Gamma_{12}(0) = 0$), prior work has indicated that values of $\Gamma_{12}(0) \approx 0.3$ are sufficient for image reconstruction of a small set of metallic objects [9], thus the measured values indicate that incoherent imaging can feasibly be implemented with the measured noise transmitter. While presenting the results of one type of noise waveform, this paper represents

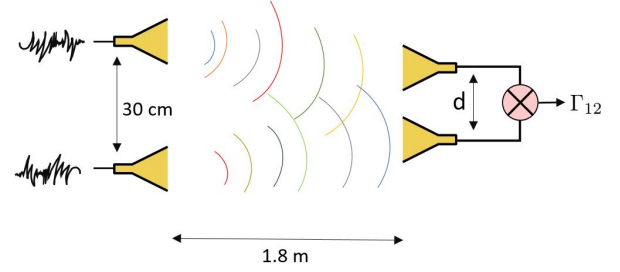


Fig. 1. Schematic of the experimental configuration for the coherence measurements.

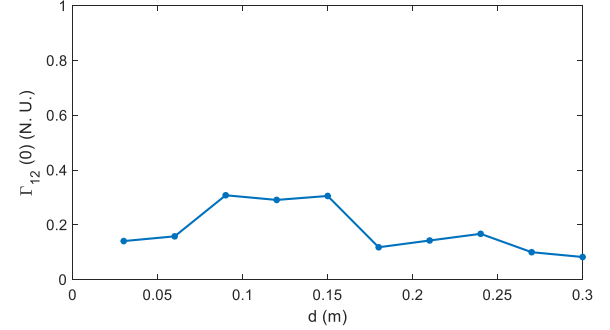


Fig. 2. Experimental results of spatial coherence. The value $\Gamma_{12}(0)=1$ corresponds to perfect coherence and the value $\Gamma_{12}(0)=0$ to perfect incoherence.

a starting point for simplified measurements of coherence in millimeter-wave imaging systems, and one that can provide coherent and incoherent systems design with a new class of amplitude and phase measurements.

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