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Point-Spread-Function (PSF) Characterization of a 340 GHz Imaging Radar using Acoustic Levitation

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Abstract—In this paper, resolution characterization and beam analysis of a 340 GHz imaging radar are demonstrated by means of a point-spread-function (PSF) study by imaging an acoustically levitated point-like target. It is shown that at THz frequencies, conventional PSF measurement techniques are limited by the presence of strong scattering response of background objects, such as suspension threads, within the imaging field-of-view (FOV). Using acoustic levitation, it is possible to eliminate secondary objects within the FOV and achieve a pure PSF characterization of the radar. It is shown that the PSF patterns obtained using acoustic levitation exhibit high fidelity and are free from artifacts. We demonstrate this using a small water droplet suspended in air at the focus of the 340 GHz radar. The measured PSF characteristics of the radar are in excellent agreement with physical optics (PO) simulations and analytical results.

Index Terms—Radar, submillimeter, acoustics, point-spread-function (PSF), acoustic levitation, imaging, antenna, beam.

I. INTRODUCTION

Imaging using electromagnetic (EM) waves has been the subject of much research and proven to be useful across a large number of applications, from through-wall imaging [1-5], to non-destructive testing [6, 7], biomedical imaging [8-11] and security-screening [12-22]. Historically, EM imaging has mostly involved the microwave and millimeter-wave regimes because of trade-offs between penetration, antenna size, imaging resolution, losses, signal-to-noise ratio (SNR) and component cost. For applications that prioritize imaging resolution and small antenna size, it might be beneficial to operate at higher frequencies. The traditional THz regime of the electromagnetic (EM) spectrum, 0.3 THz – 3 THz, brings several advantages, including large bandwidths improving the range resolution, high spatial resolution that can be achieved using relatively small sized antennas and non-ionizing radiation. However, a major factor that has prevented the submillimeter-waves from being widely adopted in imaging applications has been the lack of mature technology available at these frequencies. Over the last couple of decades, considerable progress has been made in THz electronics that has resulted in several imaging systems operating at submillimeter-wave frequencies [23-37].

The beam shape and imaging resolution of a radar can be assessed by analyzing its point-spread-function (PSF) response using a point scatterer as an imaging target [18, 38, 39]. Metal beads with a size smaller than or on the order of the radar resolution can be used to achieve this goal [15-18, 25]. However, using this approach, the reconstructed PSF pattern includes not only the contribution of the point scatterer, but also the objects that are used to suspend the point scatterer at its position within the imaging domain. Such distortions can significantly degrade the fidelity of the reconstructed PSF patterns at THz frequencies.

In this work, we demonstrate the application of a low-cost acoustic levitator [40-42] to obtain the PSF characterization of a 340 GHz radar system developed by the Jet Propulsion Laboratory [23-25]. A small droplet of water is levitated and used as the point scatterer to be imaged. The reconstructed PSF pattern is compared to the PSF pattern obtained using a metal bead suspended by a thread, and it is shown that the PSF pattern obtained with the acoustic levitator exhibits good SNR, high fidelity and is free from artifacts. The outline of this paper is as follows: In Section II, the THz radar together with the imaging process leveraging the acoustic levitator is described. In Section III, the PSF characterization of the THz radar is shown. Comparisons between different PSF characterization methodologies are demonstrated. The PSF patterns of the 340 GHz radar are compared to numerical and analytical results. Finally, in Section IV concluding remarks are provided.

II. THZ RADIAR, ACOUSTIC LEVITATION AND PSF CHARACTERIZATION

A. THz Radar

The THz radar is a frequency-modulated-continuous-wave (FMCW) system, transmitting a chirped signal centered around 340 GHz. The block diagram of the RF backend and submillimeter-wave frontend hardware architectures together with a picture of the radar is shown in Fig. 1.

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then frequency-multiplying by a factor of 18.

The transmitted FMCW waveform has a bandwidth of $\Delta f = 354.6-325.8 \text{ GHz} = 28.8$ with a chirp time $t_{\text{chirp}} = 82.5 \mu s$. This results in a chirp rate of $K = 349 \text{ MHz/\mu s}$. The IF signal is offset from DC baseband by $f_{\text{IF}} = 2Kd/c$, where $d = 5.3$ m is the total path length (one-way), which is the combination of the target distance (4 m) and the beam path length in the quasi-optics chain (1.3 m), and $c$ is the speed of light, resulting in $f_{\text{IF}} = 12.3 \text{ MHz}$. This IF signal can easily be digitized using modern analog-to-digital (ADC) converters. Data acquisition is achieved using a National Instruments DAQ connected to a host machine with Labview software (National Instruments, Texas) and a field-programable-gate-array (FPGA). The measured I and Q data from the IF chain is Fast-Fourier-Transformed (FFT) using the FPGA board, producing a 1024-point spectrum of range bins for each spatial sampling point across the imaged field-of-view (FOV). The range resolution of the radar is determined by the bandwidth of the transmitted FMCW waveform as $\delta_r = \frac{c}{2\Delta f} = 0.52$ cm. Each bin of the calculated spectrum corresponds to one range resolution cell. The extraction of the PSF patterns from the range profiles is achieved by choosing the maximum intensity in the corresponding range bins in the vicinity of the imaged target.

The transmit and receive antennas are diagonal horns sharing the same primary reflector illuminating the scene and collecting the received signal from the imaged object. The scene is raster scanned in the elevation and azimuth axes using two flat mirrors mounted on rotary motors (azimuth and elevation). The optics design is depicted in Fig. 2.

As shown in Fig. 1, in the transmit chain, a 16 GHz local oscillator (LO$_1$) is mixed with a 1.9-3.5 GHz chirp source. The mixed signal goes through several power amplifiers and frequency multipliers and is transmitted at 322.2 – 351 GHz frequency band. The signal reflected from the imaged object is received by the radar optics and fed to a mixer for down-conversion. The local oscillator for the receive chain (LO$_2$) is 16.2 GHz, 200 MHz offset from the LO frequency of the transmit chain, $f_{\text{LO}} = 16$ GHz. The receive chain has the same power amplifier and frequency multiplier configuration as the transmit chain, and operates at 325.8 – 354.6 GHz frequency band. The down-converted IF signal is centered at 3.6 GHz, which is mixed with a 3.6 GHz signal that is produced by mixing the tapped off signals from LO$_1$ (16 GHz) and LO$_2$ (16.2 GHz) sources in the transmit and receive chains, and

![Fig. 1. (a) Block diagram of the 340 GHz radar’s RF backend and submillimeter-wave frontend chains showing the generation of the transmit signal and the down conversion of the received signal to the IF baseband. (b) Experimental setup with the three main building blocks of the radar: optics, RF backend and submillimeter-wave hardware.](image)

![Fig. 2. Quasi-optics design of the 340 GHz radar. Duplexing of the transmit and receive channels is achieved using a silicon wafer while the FOV is scanned using rotating mirrors in the elevation and azimuth axes.](image)
B. Acoustic Levitator for PSF Analysis

The acoustic levitation principle has been shown to be promising in a variety of applications, ranging from studying cloud particles [43] to remote detection [44], Raman spectroscopy [45] and wireless power transfer [46]. The acoustic levitator is an inexpensive commercial product [40-42] and is shown in Fig. 3. It consists of two parabolic surfaces, top and bottom, with an array of transducers placed on each surface. The transducers are fed using a 40 kHz square-wave signal generated by an Arduino microcontroller. The transducers on each parabolic surface are in phase. Such a geometry enables the creation of acoustic standing waves between the top and bottom surfaces, giving rise to peaks and nulls between the two surfaces.

Fig. 3. Acoustic levitator for PSF analysis of the 340 GHz imaging radar.

Placing an object at the null of the acoustic standing wave enables the object to be trapped at that position, and this process is called acoustic levitation. The application of this principle for PSF characterization of the radar is low-cost and easy to set up. The acoustic levitator used in this work can levitate objects with a density of up to 2 g/cm$^3$.

III. PSF Analysis, Results and Discussion

Imaging resolution of a radar can be characterized by analyzing the full-width-at-half-maximum (FWHM) of the PSF pattern [38, 47]. The 340 GHz radar performs imaging in a two-way process, involving illuminating the target and receiving the reflected signal. As the 340 GHz radar has a monostatic system layout, the measured PSF pattern of the radar is equivalent to the multiplication of the beam pattern of the primary reflector antenna for the transmit and receive chains. This suggests that the PSF pattern is correlated to the one-way beam pattern of the reflector antenna by the square of the beam pattern. As a result, characterizing the PSF pattern of the radar also enables us to characterize the beam pattern of the radar antenna.

The PSF characterization of the 340 GHz radar was first studied using a metal bead (1 mm diameter) suspended on a thread as shown in Fig. 4(a). The target is placed at the focal distance of the primary reflector, $d=4$ m, and the scene is raster scanned within a FOV of 0.7°. Given the monostatic nature of the 340 GHz radar, in order to reduce the specular reflections of the thread in the direction of the antenna beam, the thread was rotated by 20° in the elevation axis as shown in Fig. 4(b).

![Fig. 3. Acoustic levitator for PSF analysis of the 340 GHz imaging radar.](image)

![Fig. 4. Imaging setup for a metal bead (1 mm diameter) secured with a thread at the focus of the radar for PSF analysis. (a) Thread placed facing directly the primary reflector. (b) Thread is rotated by 20 degrees to reduce the specular reflection in the direction of the primary reflector.](image)
object in a different direction. As a result, this technique has considerable limitations. Nevertheless, it can be considered useful to observe the effect of background objects in the radar beam characterization at THz frequencies, even if the specular reflections are minimized by means of adjusting the geometrical alignment of these objects.

Fig. 5. PSF pattern of the 340 GHz radar obtained using a metal bead attached to a thread. (a) The PSF pattern is shown for the metal bead attached to the thread rotated to minimize the specular reflections in the direction of the antenna beam. Distortion in PSF is highlighted in dashed circle. (b) The PSF pattern for the thread not rotated (colorbar scale is dB). (c) 1D cuts along the elevation and azimuth directions of the PSF pattern with rotated thread.

In Fig. 5, we demonstrate the PSF patterns for two different scenarios. In Fig. 5(a), the PSF of the metal bead placed on the 20° rotated thread is shown. In Fig. 5(b), the PSF pattern of the same metal bead placed on the same thread is shown, but without any thread rotation. The PSF pattern in Fig. 5(b) is heavily distorted by the specular reflection of the thread, with no distinct image of the point scatterer. Comparing Figs. 5(a) and 5(b), it is evident that the effect of the thread on the measured PSF pattern has been reduced significantly by tilting the thread to minimize the specular reflections in the direction of the antenna beam. However, as highlighted in Fig. 5(a), the obtained PSF pattern is still affected by the presence of the thread used to position the metal bead in the elevation direction. In Fig. 5(c), the FWHM values of the PSF pattern (or spatial resolution) along the azimuth and elevation directions are measured to be 0.108° (7.54 mm) and 0.131° (9.14 mm), respectively. Given the maximum frequency of the transceiver chain, 354.6 GHz, the expected PSF FWHM value at the focal plane of the primary reflector at \( d=4 \) m is calculated using a physical optics (PO) simulation software, GRASP (Ticra, Denmark). The PO simulated FWHM value is found to be 0.112° (7.8 mm). From Gaussian optics [48, 49], the theoretical FWHM value is calculated to be 0.106° (7.4 mm). It should be noted that for the PO simulation and Gaussian optics result, first, the one-way beam pattern of the primary reflector antenna at the focal plane is calculated. Following, to be consistent with the two-way imaging measurements from the radar, the simulated and analytical one-way beam patterns are squared. Therefore, the analytical and simulated FWHM analyses are performed on the squared one-way beam patterns. Whereas the FWHM value of the radar beam waist along the azimuth direction exhibits good agreement with the analytical and simulated values, in the elevation direction, due to the distortion caused by the thread, the FWHM characteristic of the PSF pattern is significantly wider than the expected values. The PSF SNR level in Fig. 5(c) is measured to be greater than 40 dB.

From these results, it is evident that alternative techniques are needed to achieve a more accurate characterization of the radar system. Although the demonstration involves a monostatic radar, our goal in this paper is to seek a cost-effective and simple technique that could be implemented to any system layout: monostatic, bistatic, or multistatic.

For the scenario studied in Fig. 4, an ideal case would be the elimination of the secondary background objects (thread) within the FOV. However, using this setup, achieving this goal is not feasible as the metal bead needs to be secured within the imaged FOV. To address this challenge, we use acoustic levitation to position the imaged object and suspend it at the focus of the primary reflector of the radar. Different from the magnetic levitation principle, using the acoustic levitation technique, any material with sufficiently low density can be levitated. Due to light density of water, 1 g/cm³, combined with its strong reflection response at THz frequencies, we choose to suspend a water droplet as the point scatterer.

The imaging setup is shown in Fig. 6. A water particle of 1 mm size is acoustically levitated at the focal point of the primary reflector of the 340 GHz radar for imaging. As seen in Fig. 6, the water particle is not attached to any secondary background objects but instead is suspended in air. It should be noted that when suspended in air, initially, the size of the water droplet is about 2 mm and the droplet exhibits a rather flattened geometry (wider in azimuth than in elevation) due to the pressure waves pushing the droplet in the elevation direction. The shape of an acoustically levitated water droplet in air medium is governed by two parameters; diameter of the droplet and the strength of the acoustic field [50, 51]. Increasing the acoustic field strength increases the non-uniform pressure distribution on the surface of the droplet, resulting in an increased droplet aspect ratio. The aspect ratio is defined as the droplet size in the direction normal to the acoustic pressure waves to the droplet size in parallel to the
nodal plane. From this definition, ideally, it is desired for PSF imaging that the aspect ratio is unity. In order to minimize the flattening in the droplet shape, we keep the acoustic field strength at minimum. This is achieved by optimizing the voltage level \( V_f \) provided to the acoustic levitator to generate the acoustic fields of minimum strength which is enough to achieve the levitation, \( V_f = 9.5 \) V. Moreover, as shown in [50], for a fixed acoustic field strength, reducing the size of the water droplet improves the uniformity of the aspect ratio. Therefore, imaging is performed after evaporating the droplet down to 1 mm diameter, minimizing the flattening in shape and ensuring that the droplet has the same size as the metal bead. The droplet-measured PSF pattern of the radar is shown in Fig. 7.

From Fig. 7(a), it is evident that no distortions due to a secondary background object are present in the reconstructed PSF pattern. Careful investigation of the reconstructed PSF pattern reveals that the PSF pattern is slightly wider in the elevation direction. This can be attributed to the offset feed of the transceiver primary reflector antenna in the elevation direction. Indeed, the PO analysis of the quasi-optics chain in GRASP reveals that the PSF FWHM in the elevation direction is \( 4\% \) wider in elevation than the FWHM in the azimuth direction. (The previously mentioned \( 0.112^0 \) (7.8 mm) beam FWHM for the PO analysis is the averaged FWHM value of the beam in the azimuth and elevation directions.)

Analyzing the 1D cuts along the azimuth and elevation directions, the SNR is measured to be greater than \( 38 \) dB, close to the SNR level achieved from the metal bead scenario but without the secondary distortions in the PSF pattern. The spatial resolution of the radar is obtained by means of analyzing the FWHM points of the 1D PSF patterns along the azimuth and elevation axes, which are measured to be \( 0.109^0 \) (7.6 mm) in azimuth and \( 0.110^0 \) (7.7 mm) in elevation, respectively, exhibiting good agreement with the PO simulation result, \( 0.112^0 \) (7.8 mm), and the analytical Gaussian Optics result, \( 0.106^0 \) (7.4 mm).

![Image](image_url)

**Fig. 6.** Imaging setup showing the water droplet acoustically levitated at the focus of the primary reflector of the radar.

**Fig. 7.** PSF of the radar obtained from a water droplet levitated using the acoustic levitator (a) 2D PSF pattern (b) 1D cuts along the elevation and azimuth directions.

### IV. CONCLUSION

PSF analysis of a radar plays a crucial role in assessing the imaging characteristics of the radar. We have analyzed the beam characteristics of the 340 GHz radar developed by the Jet Propulsion Laboratory. It has been shown that using the conventional PSF measurement techniques, such as a point scatter attached to a thread, results in distorted PSF patterns due to strong reflections from the background objects at THz frequencies. In order to address this challenge, we have leveraged the acoustic levitation principle. Relying on the standing waves generated by the acoustic levitator, we have shown that a water droplet can be levitated at the focal point of the 340 GHz radar, forming an excellent target to resolve the PSF pattern of the radar. It has been demonstrated that the water droplet provides a comparable dynamic range to a metal bead for imaging at 340 GHz but presents no distortions caused by the presence of additional objects within the FOV. Although shown for a monostatic system layout, the presented technique can readily be employed to resolve the PSF characteristics of bistatic and multistatic radar architectures.
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REFERENCES


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Dr. Yurduseven was the recipient of an Academic Excellence Award from the Association of British – Turkish Academics (ABTA) in London in 2013. He also received a best paper award at the Mediterranean Microwave symposium in 2012 and a travel award from the Institution of Engineering and Technology (IET). In 2017, he was awarded a NASA Postdoctoral Program (NPP) Fellowship administrated by Universities Space Research Association (USRA) under contract with NASA. In 2017, he received an Outstanding Postdoctoral Award from Duke University and a Duke Postdoctoral Professional Development Award. He is a member of the European Association on Antennas and Propagation (EuCAP).

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