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Augmented reality terahertz (AR-THz) sensing and imaging with frequency-modulated continuous-wave radar

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Abstract. Terahertz Imaging is one of the most promising approaches for non-destructive control. An interesting approach to having cost-effective systems is to use frequency-modulated continuous wave (FMCW) radars with a raster scan configuration. Nevertheless, current systems using linear stages or robotic arms have the disadvantage of being heavy, requiring a long scan and not allowing a direct visualization of the result being measured. In addition, it is complex to evaluate the position of the measuring point on the real object, particularly if it is not flat. Here we propose to solve these previous challenges with a portable system combining an FMCW radar with an augmented reality (AR) interface using a smartphone. This system achieves two goals : (i) first is to achieve data acquisition in the AR environment and (ii) the second is to make possible the visualization of data, even after post-processing, in the AR environment.

Keywords: terahertz imaging, augmented reality, frequency modulated continuous wave, THz radar, sensing

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1 Introduction

Enhanced vision of the real physical world is a growing technique with applications for education [1], [2], medicine [3], [4], and more widely for science [5] and industry [6]. Since augmentation can be based on digital information, some implementations use a live measurement of invisible light, like infrared [7], [8], ultraviolet [9] or XRays [10] to augment reality. While terahertz imaging has shown interest in applications in different fields such as biomedical [11], art[12], and non-destructive testing [13], the systems are mainly based on mechanical scanners which are slow and not handy. After years of development since the 1970s, terahertz imaging [14,15] systems are heading toward a reduction in size, power consumption, and cost reduction. The development of systems based on the femtosecond system in the 90s and 2000s, then Silicon based systems in the 2010s have allowed an evolution that today leads to integrated and fast terahertz systems. An example of this evolution is the frequency-modulated continuous-wave (FMCW) radars, which were previously only available as a chain of multipliers with III/V technologies and which have been commercially available since the years 2015 - 2020 in the form of integrated CMOS systems. This opens up many applications both for the non-destructive testing of composite materials or polymers and the analysis of rocks [16-19]. Compact systems now make it possible to develop agile, low-cost systems with

the potential for wider integration and distribution, including endoscopic devices [20] and open-source projects like Teragologic [21]. However, these different approaches require a point-to-point scan that is relatively slow and not very suitable for certain experimental situations, for which a portable device and the possibility of having rapid information without contact and scanning can be obtained. Of course, these setups have the advantage of providing a mechanical precision better than the diffraction-limited resolution, and therefore to make optimal images. Still, these systems are not very practical when we want to take a quick measurement or when we want to know quickly which part of the object we are measuring. An interesting approach to overcome these limits is to use a multi-axis robotic arm, but this solution remains complex to integrate and expensive. In addition, these systems involve processing after measurement, which makes it difficult to visualize terahertz information on the real object. To meet this need for portability, handheld THz is a solution but does not provide direct visualization of the THz information [22]. Preliminary results of an augmented reality device combining an FMCW radar and a smartphone were presented [23,24] in the field of art and heritage, and this article presents this solution and the associated data processing for different study cases.

2 Experimental setups

2.1 AR-THz system

We've integrated a compact FMCW radar with an augmented reality (AR) interface to create a user-friendly mobile system [25]. As depicted in Figure 1, our setup utilizes a OnePlus 7T Pro smartphone. This device aids in determining the distance to the subject using its camera, which is crucial for focusing. Furthermore, the smartphone is responsible for both collecting data and overlaying the processed terahertz information on the live camera feed. This approach allows us not only to view the enhanced image in real-time but also to apply further analysis afterward, revisiting the scene with the terahertz signals in an augmented reality environment.

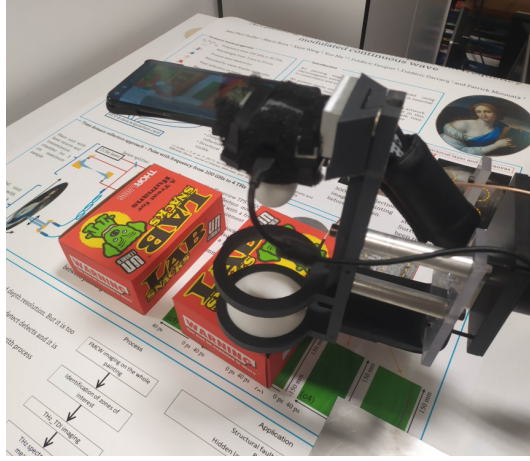


Figure 1 : AR-THz system with a smartphone and a FMCW radar

2.2 FMCW radar and integration

In short-range FMCW radar imaging, optimal retrieval of spatial information typically requires a confocal arrangement enhanced by high numerical aperture optics, such as steeply curvature lenses or parabolic mirrors, in tandem with an antenna having substantial gain characteristics. However, in the search for an economically viable and widely distributable augmented reality platform as the *Teragotic project*[2], we aspire to deviate from conventional methodologies, leveraging an original approach to democratize the application of terahertz frequency systems. The economic aspect, considered essential for this initiative, requires a re-evaluation of the selection of components to respect cost without compromising functionality. With this in mind, the traditional metal horn antenna, a component whose cost is important compared to the entire radar Si-Ge system, has been replaced by a dielectric lens antenna [3]. This substitution aligns with established precedents in application sensing paradigms, particularly those that tolerate lower-resolution outputs. Deploying a dielectric antenna introduces specific inherent limitations, including pronounced internal reflections and high sidelobe levels, which are inherent disadvantages when juxtaposed with the performance of conventional metal horn antennas. However, these limitations are mitigated in the context of our system design parameters. The radar's longitudinal resolution δ_d makes it possible to discern and then cancel out the effects of internal reflections. It can be calculated from Eq (1) with a $BW = 45$ GHz in our case, giving a longitudinal resolution of 3,3 mm.

$$\delta_d = \frac{c_0}{2nBW} \quad \text{Eq (1)}$$

Additionally, the operational requirements of the system do not require a lateral resolution of more than 5mm; instead, a significant depth of field is desirable. This extended depth of field ensures resilience against minor variations in distance between the sample and the system, a common occurrence due to the manual

positioning inherent in practical use scenarios. In this work, we will consider that the manual positioning accuracy is about 5mm, and adjust the data processing and imaging resolution accordingly.

2.3 Data processing

The conventional FMCW terahertz imaging process starts with a configuration phase, where the parameters of the terahertz system are established. This includes setting up the frequency range, resolution, and the sensitivity of the terahertz detector. Following configuration, a raster scan measurement is conducted. This method involves the systematic movement of the sample or the terahertz source in a grid pattern to collect data point by point across the sample's surface. The raster scan enables the creation of a high-resolution image by amalgamating the individual measurements, but it is time-consuming due to the serial nature of the data acquisition process.

After the data collection, post-processing is carried out. This stage is imperative in terahertz imaging as it involves the application of algorithms to improve the signal-to-noise ratio and interpret the raw data into a usable image format. Techniques such as denoising [26], super-resolution [27], or SAR [28] may be utilized to extract spatial and depth information from the terahertz signals.

Here, with an augmented reality-based approach, the flow is different, as illustrated in Figure 2 : Data processing procedure for (a) classical raster scan imaging and (b) augmented reality system.. Since we have a real-time view, we have to implement what is generally done as a post-processing at the beginning. This requires a specific implementation which depends on the object. The integration of AR technology necessitates additional calibration to ensure the alignment of virtual and physical space and also a configuration of the terahertz parameters. This allows for rapid, intuitive scanning, particularly beneficial for larger objects or areas where high resolution is not the primary concern. Finally, optional post-processing can still be employed. In this context, the post-processing may not be as extensive as in the traditional method, since the AR system can provide on-the-fly processing and visualization. However, further processing may still be applied to refine the data for specific applications or to analyze the information more deeply.

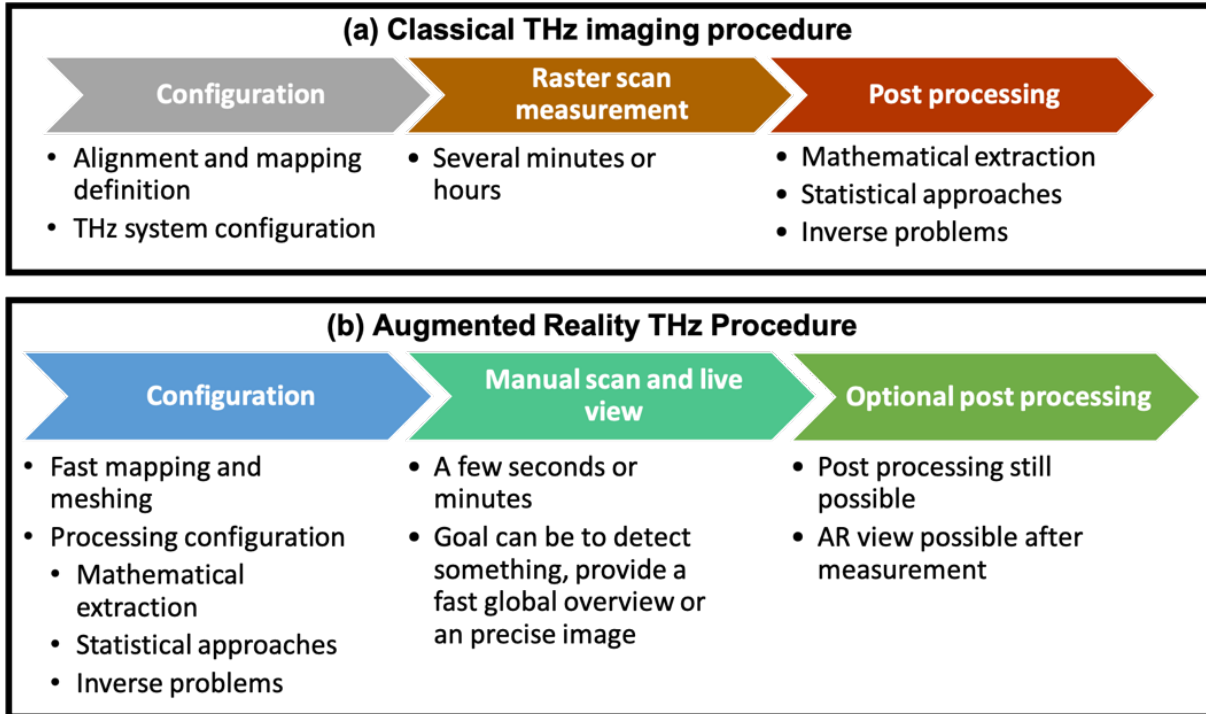


Figure 2 : Data processing procedure for (a) classical raster scan imaging and (b) augmented reality system.

2.3 Objects under investigation and related processing configuration

Our research focuses on two distinct case studies that highlight the imperative for instantaneous processing capabilities for (AR-THz) imaging. Each is accompanied by their respective signal processing configurations tailored to unique challenges presented by the objects studied. The first case study focuses on a painting beneath which a metallic plate has been positioned, illustrating the utility of AR-THz in cultural art and heritage conservation, where the objective is to non-invasively detect and visualize artifacts or defects. In that case, the THz signal processing configuration will be calibrated to distinguish the high reflectivity of the metallic object against the less reflective backdrop of the painting's substrate. The second case study involves a box filled with confectionery items, to demonstrate the potential of AR-THz sensing in quality control and security screening, where the contents of a package may need to be assessed without opening it. The processing configuration for this case will be optimized to detect the absence of a strong reflective signal indicative of the presence of food, which absorbs and scatters the THz waves, thereby providing contrast against the reflective properties of the container itself.

2.3.1 First study case: hidden metal plate – Maximum peak detection

We focus first on the artwork depicted in Figure 3. Beneath the area of the painting corresponding to the subject's mouth, a metallic plate has been placed at a depth of 5 mm from the painted surface. The primary

aim of this experimental setup is to conduct a swift scanning procedure to detect the presence of this metal object. Given the shallow placement of the plate and the specific goal of detection rather than high-resolution imaging, we employ a simplified signal processing approach. This method involves the extraction of the maximum peak amplitude within the acquired signal profile, without any information about the distance. Depending on the measured area, this peak may correspond either to the THz wave reflected by the paint layer itself or to the wave that has interacted with the underlying metal object.



Figure 3 : (a) Scheme of the experiment. (b) Photography of the painting. The metal plate is placed below the mouth of the woman in the painting.

2.3.2 Second study case: food box – Second peak with self-referenced detection

The second experiment consists of determining which of the two boxes illustrated on the Figure 4 is empty or filled with treats. In the case of an empty box, the terahertz wave is reflected on the initial cardboard interface, propagates inside the box, and then is reflected by the second interface located at the rear limit of the box. Conversely, when the box is filled with confectionery, the propagating wave is subject to absorption and diffusion within the contents, resulting in the absence of a second perceptible echo, or at all the least, a noticeably attenuated echo. This phenomenon provides a qualitative metric to check the presence of objects in the box.

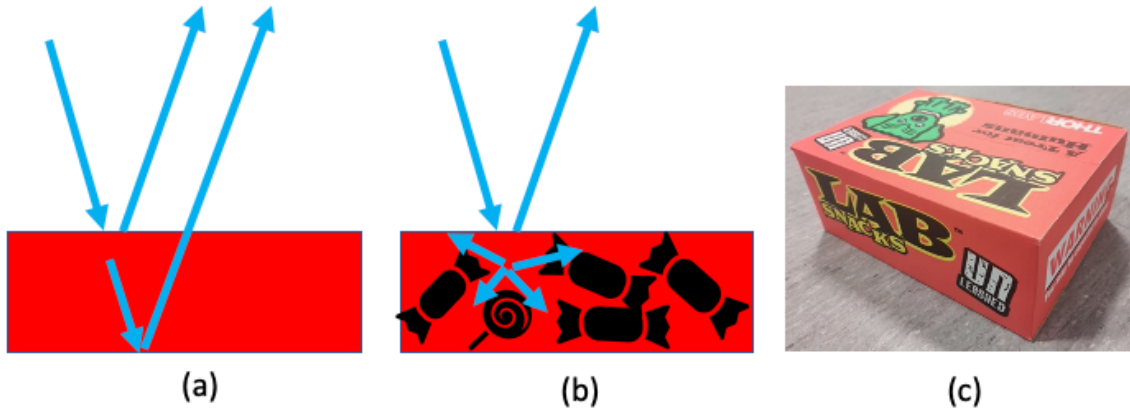


Figure 4 : Boxes under investigation

Given the greater complexity of this situation compared to case 1, we will use different signal processing. In this case, we will first look for the first reflection peak on the first layer of cardboard, providing a working range with a margin of 5cm, facilitating positioning for the user. Then, an interval of 1 cm is extracted 6 cm below this first interface, and the maximum of this area is extracted and transmitted as an analog value to the smartphone.

3 Results and discussion

The result for the first case study is rapid metal plate detection, as shown in Figure 5, which is an augmented reality view taken from the phone during the measurement. A quick manual scan of less than a minute allows to capture several points around the mouth and identify a red zone, corresponding to a strong reflection. We therefore quickly obtain a contrast compared to the surroundings and the rest of the painting which is young or green in color depending on the settings of the color scale. This technique therefore allows a measurement halfway between imaging and puncture detection, with high agility and rapid resolution, nevertheless with a resolution lower than what would be obtained with a point-by-point scan with a system optimal optics.

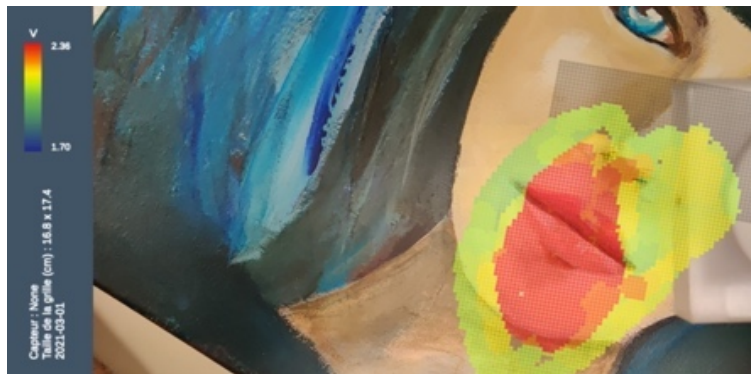


Figure 5 : AR THz measurement of the painting with a metallic plate below the mouth of the subject.

The utility of this simplified approach lies in its expedited analytical capacity, permitting rapid assessment that is particularly advantageous in scenarios where time-efficient methods are paramount. Additionally, it offers a non-invasive technique to identify potential artifacts or interventions beneath the paint layer, which could be integral to authentication processes or conservation efforts. The delineation between the two potential maxima—the painted interface or the metal object—will be discernable in the amplitude signal, thereby allowing for effective detection of the metallic plate without necessitating a comprehensive analysis of the entire signal profile.

The results of the second study case are presented in Figure 6, with different views corresponding to the different measurement steps, which makes it possible to show in detail the acquisition procedure and the associated results. We discuss each step of the measurement and the result:

- (a) Scene Overview with Two Boxes: This initial phase allows for calibration of the gain and sensitivity of the system to meet the specific requirements of the scene under examination. At the base of Figure 3(a), we can see graphical information of the signal intensity post-implementation of the previously detailed signal processing process.
- (b) Meshing Procedure: This step entails a swift, non-acquisitive scanning of the entire scene. It is required by the AR Core library for the identification of distinctive elements within the scene. After this identification, a mesh is generated, allowing for the three-dimensional localization of the system within the environment.
- (c) Measurement on the Right Box: Observations of the right box reveal a predominance of red in the sensor's output, meaning the box is empty.
- (d) Measurement on the Left Box: In contrast, the left box measurement is characterized by a blue sensor output. The decrease in signal strength from the second interface suggests the presence of content in the box. This is noticeable in real-time as the measurement probe fills the space with the collected data values.
- (e) Scene Overview with Superimposed THz Processing Data: This perspective offers a comprehensive view of the scene post-measurement. It features an overlay of the THz signal data upon the visual representation of the objects, thereby illustrating the integration of THz imaging data with the physical scene.
- (f) Opening the Left Box with Maintained Tracking: Upon opening the left box, the tracking is preserved, revealing the presence of food items within.
- (g) Opening the Empty Right Box: The right box, when opened, confirms its emptiness as previously indicated by the THz signal analysis.

(h) Backward Movement and Rotation with Continuous Tracking and THz Data: The system demonstrates its ability to maintain consistent tracking and THz data integration even when the user engages in backward movement and rotation relative to the scene.

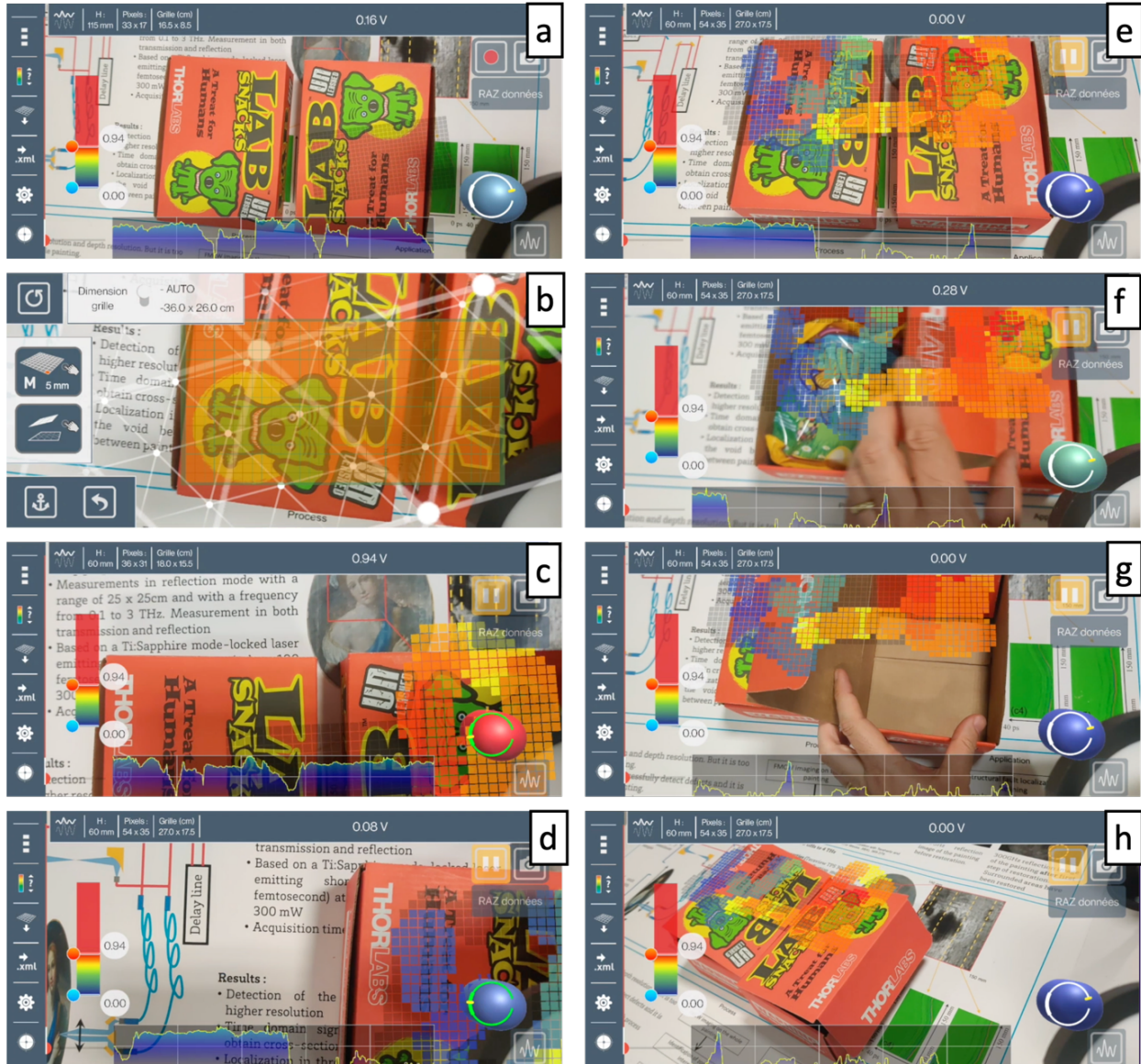


Figure 6 : Screenshots of the measurement sequence from the Smartphone from a video. (a) Overview of the scene with the two boxes (b) Meshing procedure (c) Measurement on the box at the right, we can see that sonde is red (d) Measurement on the box at the left, we can see that sonde is blue (e) Overview of the scene with THz processing data superimposed in 3D (f) Opening the left box, while tracking is maintained, there is food (g) Opening the box on the right which is empty, (h) Backward movement and rotation while keeping the tracking and the THz information

4 Conclusion

In conclusion, the integration of FMCW radar with a smartphone-based augmented reality interface heralds a transformative leap in the arena of compact and hand-held terahertz systems for sensing and imaging. As evidenced by our two study cases, this innovative integration not only streamlines the user interface but also markedly diminishes the temporal and procedural intricacies that are characteristic of conventional terahertz imaging methodologies. The technology harbors versatile potential applications, including but not limited to, the preservation of cultural artifacts, enhancement of quality control protocols, security screening, and contributions to civil engineering—each benefiting from rapid, non-invasive inspection capabilities.

This pioneering AR-THz integration lays the foundational framework for the advent of a novel class of terahertz imaging instruments that boast portability, cost-effectiveness, and user-centric design—thus, overcoming the constraints imposed by traditional mechanical scanning devices and broadening the horizons for widespread adoption and utilization. The nimbleness and instantaneous processing prowess of our system make it an especially advantageous tool for on-site analysis. In such cases, prompt feedback and operational simplicity are of the essence. Although the resolution may not rival that achieved by more intricate point-by-point scanning systems, the practical benefits of our methodology endow it with significant merit within the terahertz imaging technologies. Prospective endeavors will concentrate on the enhancement of the system's functionalities, integration of more advanced signal processing functionalities, and the promotion of terahertz technology accessibility for both professional and educational use.

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