Overview of Terahertz 3D Imaging Technology

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Abstract. Terahertz three-dimensional imaging system can realize the detection and imaging of near-field targets with high frame rate and high resolution, and can provide more comprehensive information about the three-dimensional geometric distribution structure of the target and the imaging scene. It is suitable for the current high real-time requirements Security inspection, seeker terminal guidance, military reconnaissance and other fields. The high-resolution three-dimensional imaging technology of radar targets in the terahertz band is of great significance to the development of radar technology and the application of radar imaging. In this paper, the research background and significance of the terahertz near-field imaging technology, radar three-dimensional imaging technology, the development status of terahertz radar system and terahertz radar imaging algorithm are reviewed, and the existing problems of terahertz near-field imaging technology are summarized and prospected.

Keywords: Terahertz radar · Three-dimensional imaging · Time domain imaging algorithm · Frequency domain imaging algorithm

1 Introduction

Terahertz (THz) waves refer to electromagnetic waves with frequencies in the range of 100 GHz to 10 THz. They are between millimeter waves and infrared, called sub-millimeter waves or far-infrared light, and are in the transition zone from electronics to photonics. Compared with signals in the microwave and millimeter wave bands, the wavelength of the terahertz band is relatively short, which is more conducive to achieving large signal bandwidth and narrow antenna beams, and can obtain fine imaging of the target [1–3], which is very conducive to target identification. Compared with infrared light signals, terahertz waves have stronger transmission ability for non-polar and weak-polar media materials, can penetrate clouds and smoke, see through camouflage, and are suitable for complex battlefield environments, and the echo has better Coherence, with higher anti-interference ability.

Terahertz technology can also be used to detect dangerous goods and hidden objects and perform imaging. Because terahertz radiation is non-ionizing, it can penetrate materials that are opaque to other frequency bands, such as packaging materials, clothes and walls. These properties of terahertz port make terahertz remote sensing better used in non-destructive applications. Testing and safety inspection.

In recent years, with the continuous improvement of the performance of terahertz devices, the research and development of terahertz application systems has gradually

S. Shi et al. (Eds.): AICON 2020, LNICST 356, pp. 517–530, 2021.
https://doi.org/10.1007/978-3-030-69066-3_46

attracted the attention of countries all over the world. Terahertz science and technology have been recognized by the international scientific community as a strategically significant field and will gradually become a battleground for high-tech industries.

2 Radar 3D Imaging Technology

At present, based on traditional SAR and ISAR imaging technologies, radar systems with three-dimensional imaging capabilities mainly include: Interferometric SAR (InSAR), Interferometric SAR (InISAR), Circular SAR (CSAR), tomographic SAR (TomoSAR), array 3D SAR, and array 3D ISAR. InSAR and InISAR both use multi-antennas and interferometric processing technology to achieve 3D imaging of the observation scene based on 2D imaging. Circular SAR and tomographic SAR are The synthetic aperture formed by the radar trajectory is used to realize the resolution in the height direction, while the array 3D SAR and the array 3D ISAR use the real apertures formed by the antenna array to obtain the resolution of the third dimension. The following mainly discusses and briefly discusses these three types of imaging technologies analysis.

2.1 Interferometric 3D Imaging

The concept of interferometric processing technology is to extract the phase difference of the same resolution unit through a single observation of multiple antennas or multiple observations of a single antenna to obtain the information of the observed resolution unit in the vertical line of sight and the direction of the flight path. Image-based, to achieve three-dimensional imaging of the observation area or target. In 1974, L.C. Graham first proposed the use of interferometric SAR for three-dimensional measurement and introduced the imaging principle of interferometric SAR [4]. With the development and advancement of radar technology, interferometric SAR imaging technology has become more mature, and many interferometric SAR processing methods have been studied in depth. Zhenfang Li et al. proposed a method for estimating synthetic aperture in the presence of large co-registration errors. A new method of radar interference phase, which uses the coherent information of adjacent pixel pairs to automatically register the SAR image, and uses the joint signal subspace to project to the corresponding joint noise subspace to estimate the terrain interference phase [5]. PAN Zhou-Hao et al. improved the three-baseline phase unwinding method based on clustering analysis and solved the problem of elevation inversion in the sudden elevation region of the scene [6]. Today, these interferometric SAR processing methods have been widely used in terrain surveying and mapping, moving target detection and positioning, and ocean monitoring.

InISAR is based on ISAR imaging of multiple antennas perpendicular to each other and uses interference technology to reconstruct the three-dimensional coordinates of the scattering points on the target. In 1996, M. Soumekh et al. proposed the use of an interferometric algorithm for dual-channel ISAR image processing. The algorithm has sufficient accuracy to use the phases measured by ISAR single and dual stations for interference processing [8]. In 2007, Lincoln Laboratories built a multistatic radar interferometric imaging test system, which verified the three-dimensional imaging capabilities of interferometric ISAR through the processing of one-shot and three-recovered wave data. In 2014, the University of Pisa in Italy conducted a dual-antenna interferometric ISAR imaging experiment, which realized the interferometric three-dimensional measurement of trucks, but the imaging results only contained strong scattering points [8, 9]. Domestically, many units have also carried out research on InISAR imaging. Among them, Northwestern Polytechnical University proposed a close-range high-resolution microwave imaging method, and carried out imaging experiments on aircraft models in a microwave anechoic chamber, and realized the aircraft The interferometric 3D imaging of the model verifies the feasibility of this method [10].

The advantage of the interferometric three-dimensional imaging technology is that the number of array elements is relatively small and the interferometric measurement accuracy is high. However, the interference processing technology assumes that only one scattering point is included in the same resolution unit. Only one elevation information can be calculated through the interference phase between antennas, so there is no resolution ability for scattering points in the same distance unit.

2.2 Synthetic Aperture 3D Imaging

The synthetic aperture formed by the circular trajectory of the radar movement or the multiple trajectories that enable the radar to achieve three-dimensional resolution based on the SAR two-dimensional imaging is called the synthetic aperture three-dimensional imaging technology, including circular SAR and tomographic SAR. In 1996, M. Soumekh first proposed the circular SAR imaging mode, and then analyzed its three-dimensional imaging capabilities [11, 12]. In 2004, Per-Olov Frölind et al. carried out the first airborne CSAR test. Compared with linear tracking SAR, the detection performance has been significantly improved [13]. In 2006, the U.S. Air Force Laboratory carried out a series of CSAR airborne tests and published Gotcha data to achieve high-resolution 3D imaging of the detection target.

Tomography SAR draws on computer tomography (CT) technology. It uses the synthetic aperture formed by radar in the vertical line of sight and azimuth and combines the principle of three-dimensional tomography to achieve three-dimensional imaging. In 1998, the German Aerospace Agency first carried out the experiment of polarization airborne SAR tomography, which verified the feasibility of airborne tomographic 3D SAR imaging [14]. In 2004, G. Fornaro et al. used the data of 30 voyages of the ERS satellite to achieve 3D imaging of the São Paulo Stadium in Italy, thus verifying the feasibility of spaceborne 3D tomographic SAR [15].

Compared with interferometric SAR, synthetic aperture 3D imaging technology can distinguish multiple scattering points in the same range-azimuth resolution unit, which can realize true 3D imaging, and the system is simple to implement. However, the synthetic aperture 3D imaging technology requires high trajectory accuracy of the flight platform, and the image registration is difficult, and the system has a long accumulation time, so the image registration is very difficult.

2.3 Array 3D Imaging

Array SAR is a two-dimensional virtual array formed by cutting track array or multi-input multi-output (MIMO) antenna combined with radar motion, and the high-dimensional resolution brought by bandwidth signal to obtain three-dimensional imaging results. Work in front-view or down-view mode. In 2004, R. Giret and others of the French Aerospace Agency carried out the imaging research of the linear array 3D SAR on the UAV, and obtained the car height image in the down-view mode [16]. Beginning in 2005, the German Institute of Applied Sciences (FGAN) has carried out airborne down-view 3D SAR imaging research based on MIMO array [17], and conducted the first actual test in 2010 [18]. Domestically, the University of Electronic Science and Technology of China built a ground-based array SAR imaging experimental platform in 2008, and subsequently conducted many field experiments, and obtained the three-dimensional imaging results of the field experiments [19].

The advantage of the array 3D imaging technology is that the imaging frame rate is relatively high, but the number of array elements required by the system is very large and the cost is high.

3 Terahertz Radar Imaging System

3.1 Foreign Terahertz Radar System

The Jet Propulsion Laboratory (JPL) of the United States is an important research institution in the field of terahertz imaging and has achieved many research results. It is one of the first institutions to develop a terahertz radar system. In 2007, the laboratory successfully developed the first high-resolution terahertz radar imaging system with a working frequency of 560 GHz–635 GHz using Frequency Modulation Continuous Wave(FMCW)system, and achieved a distance resolution of 2 cm within a range of 4 m [20, 21]. In 2008, Cooper KB and others of JPL Lab successfully developed a 580 GHz active coherent terahertz radar, which uses a linear frequency modulation continuous wave system to achieve millimeter-level range resolution, and uses very narrow antenna beam scanning to achieve The centimeter-level azimuth resolution [22]. In 2011, JPL Lab improved the original experimental system and realized a three-dimensional scanning terahertz radar imaging system with a center frequency of 675 GHz and bandwidth of 29 GHz, with a maximum imaging distance of 25 m. At the same time, the system's multi-pixel scanning at the same time The method greatly shortens the imaging time. Figure 1 shows the imaging results of three PVC pipes hidden under clothes by the radar system [1]. In 2014, JPL Lab successfully developed a 340 GHz radar array transceiver and successfully applied it to a video frame rate imaging security inspection system [23]. In 2015, JPL designed and developed a radar integrated array transceiver with 8 array elements, the array size is only 8.4 cm [24, 25], which can further increase the imaging frame rate and shorten the imaging scan time.

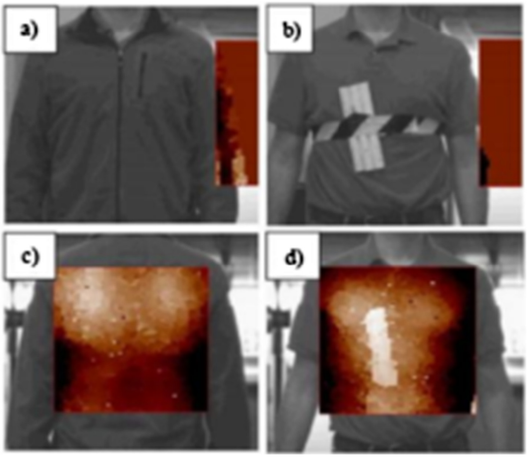

Fig. 1. 675 GHz radar imaging results of the JPL laboratory in the United States

In 2009, the Pacific Northwest National Laboratory (PNNL) developed a 350 GHz active detection imaging system. This system uses a combination of quasi-optical focusing devices and high-speed conical scanning to achieve an imaging resolution of 1 cm [26, 27]. The system can quickly detect dangerous objects hidden on cooperative targets, and can almost achieve real-time imaging. System conceptual diagram and physical diagram are shown in Fig. 2 and Fig. 3.

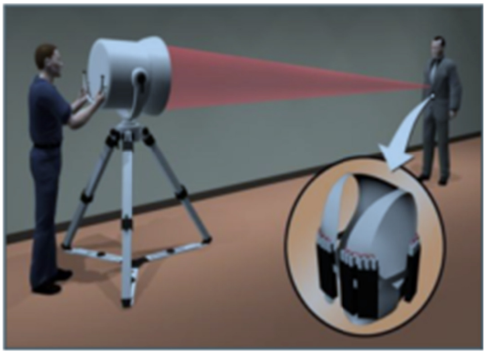

Fig. 2. Conceptual diagram of 350 GHz active detection imaging system

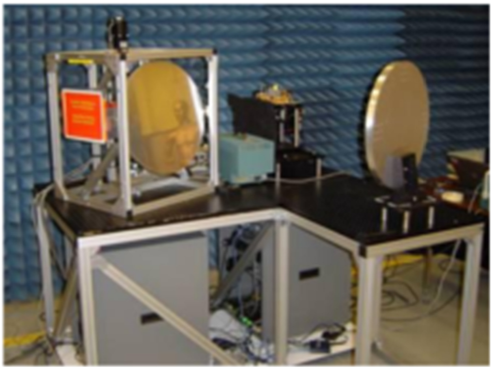

Fig. 3. 350 GHz active detection imaging system

Beginning in 2007, German FGAN has carried out a series of research on terahertz radar SAR and ISAR imaging. First, it developed the COBRA-220 radar system [28, 29], with a center frequency of 220 GHz, and carried out the development of complex targets such as bicycles and automobiles. In the high-resolution SAR and ISAR imaging experiments, the system can image a target at a distance of 135 m with a resolution of 1.8 cm. In 2013, FGAN developed the MIRANDA-300 radar system with a working frequency band of 325 GHz, with a resolution of 3.75 mm.

In 2011, & (R&S) of Germany designed a QPASS system that includes 96 transmitting antennas and 96 receiving antennas in each transceiver unit, as shown in Fig. 4. The azimuth resolution is 1.96 mm, the acquisition time of imaging data is 20 ms [30, 31].

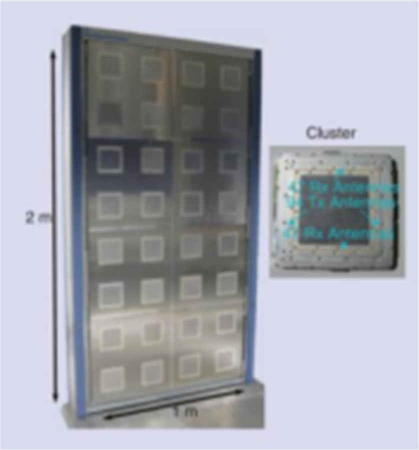

Fig. 4. The imaging system of R&S

3.2 Domestic Terahertz Radar System

Domestic research units include the Institute of Electronics of the Chinese Academy of Sciences, the Chinese Academy of Engineering Physics, the University of Electronic Science and Technology of China, and the National University of Defense Technology. In 2011, the Institute of Electronics, Chinese Academy of Sciences designed and implemented a 0.2 THz three-dimensional holographic imaging system, which is based on optical path sector scanning and one-dimensional linear scanning to achieve the three-dimensional reconstruction of the target [32, 33]. In 2012, the Institute of Electronics of the Chinese Academy of Sciences designed and developed a three-dimensional holographic imaging system with a center frequency of 0.2 THz and a sweep bandwidth of 15 GHz [34]. The imaging resolution of the system has reached 8.8 mm, realizing the 3D image reconstruction of the human body model of hidden dangerous objects under the terahertz quasi-light Gaussian beam. Figure 5 shows the simplified structure of the system and the result of imaging the model with hidden pistol targets. In the following years, the unit continued to improve the imaging algorithm and achieved good imaging results [35–38]. In 2014, the University of Electronic Science and Technology of China established a 330 GHz radar system [39], carried out turntable imaging experiments on aircraft models and other targets, and carried out equivalent CSAR imaging experiments in the terahertz frequency band, achieving three-dimensional imaging of point targets [40, 41]. At the same time, the National University of Defense Technology built a multi-band multiplexed terahertz radar system in a darkroom environment, and carried out a series of imaging experiments on turntable targets and moving targets [42–44]. In 2017, the China Academy of Engineering Physics built a 340 GHz system, using 4 transmitters 16 receivers MIMO array and one-dimensional optical path scanning to achieve 3D imaging of the human body [45, 47].

Fig. 5. 3D imaging results of a human model with a hidden pistol

4 Terahertz Radar Imaging Algorithm

4.1 THz Radar Imaging Algorithm Based on Time Domain

Time-domain imaging methods are widely used in terahertz radar imaging processing. Back-projection algorithm is the most commonly used algorithm in radar imaging technology. The principle is to back-project radar echo data to each pixel in the imaging area, and calculate the radar The distance and time delay of the echo between the radar antenna and the image pixel are cumulatively imaged. The flow diagram of the BP algorithm is shown in Fig. 6, the American JPL system in the literature [24, 25], and the early circular scanning of the PNNL in the literature [47]. The imaging system, the planar electrical scanning imaging system based on sparse matrix system of R&S company in literature [48, 49] and the 340 GHz system of China Academy of Engineering Physics in literature [45, 50] all adopt BP algorithm for imaging. The advantage of this algorithm is that it can be applied to a variety of imaging models, is not affected by imaging geometry and array form, and the imaging results are accurate, but the algorithm has a huge amount of calculation and long imaging time, which cannot meet the requirements of fast imaging.

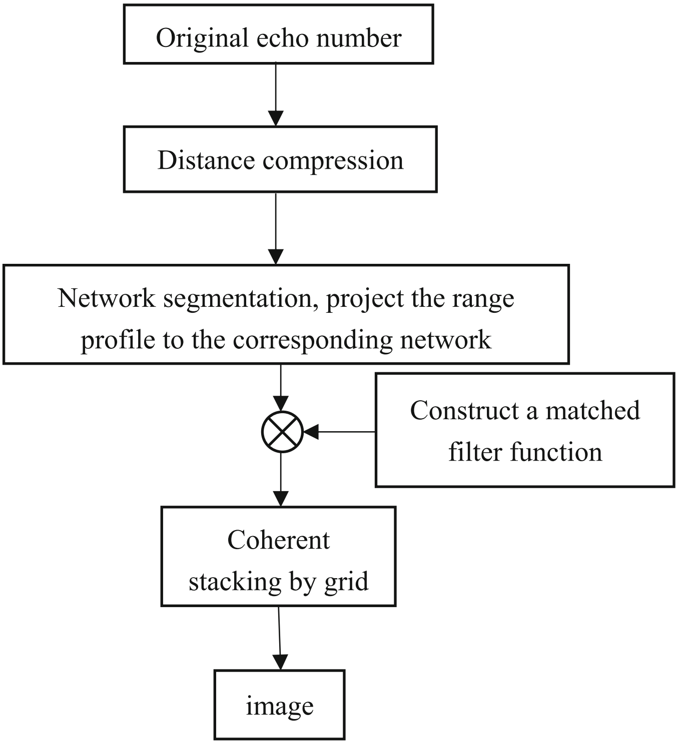

Fig. 6. BP algorithm flow

In recent years, many scientific researchers have optimized the BP imaging algorithm and promoted it to a variety of terahertz imaging systems. Among them, in the literature [51], Wang Qiong extended the BP algorithm to the MIMO linear array imaging system and realized the simulation of 5 scattering points in the scene, thus verifying the good focusing performance of the BP algorithm. Literature [52] proposed a range migration back projection (RM-BP) algorithm for near-field sparse MIMO-SAR 3D imaging. This method can achieve near-field MIMO-SAR 3D imaging focusing, and the calculation speed is greatly improved. The acceleration factor is an order of magnitude with the number of SAR-dimensional scanning arrays, but the imaging quality does not change much, which has certain advantages in practical applications.

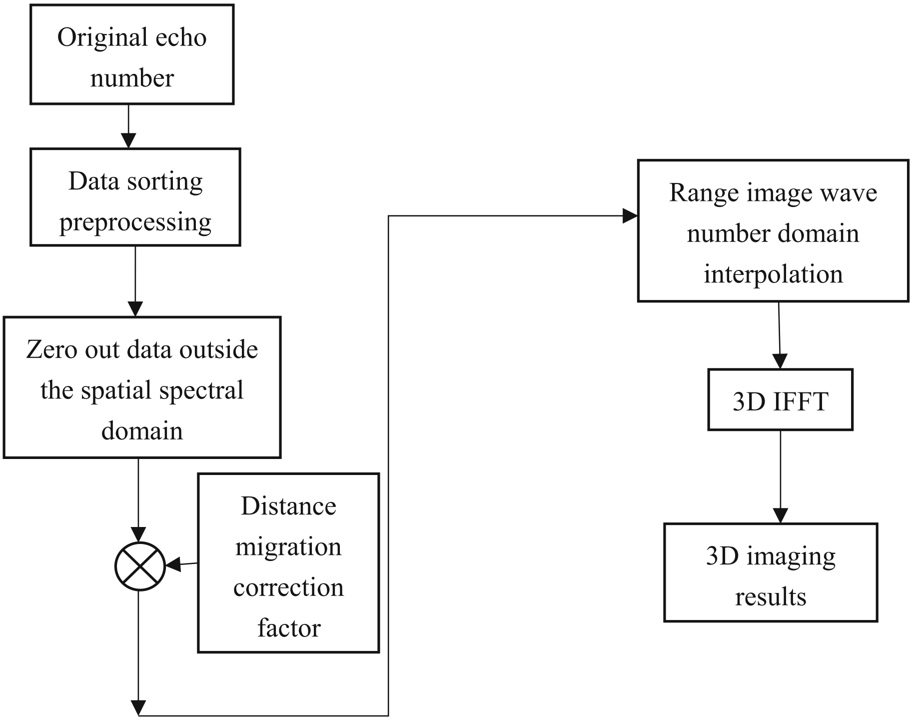

Fig. 7. 3D imaging process based on RMA algorithm

4.2 Terahertz Radar Imaging Algorithm Based on Frequency Domain

The frequency domain imaging method transforms the echo signal into the wavenumber domain space, and uses the Fourier Transform (FT) method for imaging, which greatly improves the imaging efficiency. The distance migration algorithm realizes the reconstruction of the target image in the wavenumber domain, and can achieve complete focusing without geometric deformation based on the scattering point model for the entire area without adding other approximate conditions. This method can be called terahertz near-field in principle. Optimal imaging algorithm for uniform array imaging system. The three-dimensional imaging process of near-field targets based on the RMA algorithm is shown in Fig. 7. The imaging systems in literature [53, 54] all adopt distance migration algorithms to reconstruct images of three-dimensional targets. However, the actual implementation requires the use of Stolt interpolation, which results in a very large amount of calculation and further reduces the running speed of the algorithm. The Institute of Electronics, Chinese Academy of Sciences and Tsinghua University have improved RMA [55, 56], and the processing efficiency and accuracy have been improved. n [57], Wang Youshu proposed an improved cylindrical imaging algorithm based on non-uniform fast Fourier transform (NUFFT), which reduces the influence of interpolation errors on imaging quality and improves the efficiency of the algorithm. Jiang Yanwen of the National University of Defense Technology proposed a wavenumber domain 3D imaging method based on NUFFT in [58]. From the simulation results, the 3D reconstruction accuracy of this method is very high, and the resolution ability is close to the theoretical resolution.

4.3 Terahertz Radar Imaging Algorithm Based on Range Doppler Domain

Figure 8 shows a typical algorithm-RD algorithm in the range Doppler domain. The advantage of this algorithm is that the calculation speed is fast and it can adapt to the change of the parameters with the distance. The computational complexity of the algorithm is on the order of N2, and each operation is based on one-dimensional operations, which is simple, efficient and easy to implement. At the same time, the distance migration compensation (RCMC) and other operations can be adjusted through the change of the equivalent speed V. This adaptability comes from the distance Doppler domain processing of the data. However, the disadvantage of this algorithm is that there are many compensation items. Jiang Ge et al. proposed a range-Doppler-based holographic radar imaging method in [59], which can compensate and image multiple moving targets at the same time, and the imaging speed is also greatly improved, which makes up for the existing imaging algorithms. Insufficient. Literature [60] proposed an improved range-Doppler imaging algorithm for frequency modulation FM-CWSAR. Through simulation experiments, the feasibility and correctness of the algorithm were verified, which provided a basis for further research and design of ground orbit FM-CWSAR systems. Theoretical reference basis.

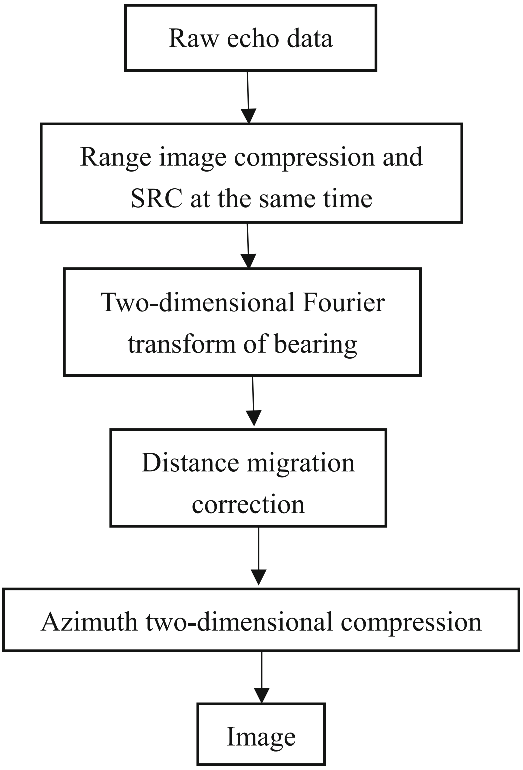

Fig. 8. RD algorithm flow

5 Summary and Outlook

Compared with traditional radars, terahertz radars have higher speed measurement accuracy, target recognition and imaging capabilities, and strong anti-jamming capabilities, as well as very good anti-stealth capabilities. Terahertz radar also has the ability to penetrate plasma to detect targets. However, judging from the development status of terahertz imaging technology, there are still many problems to be solved urgently, and serious challenges are still faced.

(1) The imaging results of the traditional BP imaging algorithm are accurate, but the algorithm has a huge amount of calculation and long imaging time. To solve this problem, we can further optimize the BP imaging algorithm to make it more suitable for terahertz three-dimensional imaging systems.

(2) The traditional distance migration imaging algorithm has the problems of long interpolation time and inaccurate interpolation, which will affect the imaging quality. It is necessary to further study the fast and accurate frequency domain imaging algorithm suitable for terahertz three-dimensional imaging system.

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