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# Rice Yield Estimation Based on Spaceborne SAR: A Review From 1988 to 2018

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**ABSTRACT** Rice is a staple food for nearly half the world's population. Therefore, rice yield estimation has far-reaching significance for food security. As the population continues to expand, rice is often in short supply. Timely and accurate data on rice production is crucial for governments and markets. Traditional rice yield estimation techniques cannot meet the current demand. With its ability to penetrate clouds and rain and the advantage of abundant remote sensing information, spaceborne synthetic aperture radar (S-SAR) can be used in the application of rice yield measurement. In this paper, the history and recent developments of rice yield measurement (1988-2018) based on spaceborne synthetic aperture radar are introduced, and the application prospect and technical development of rice yield monitoring are sought.

**INDEX TERMS** Spaceborne SAR (S-SAR), microwave remote sensing, rice yield, polarization, time phases.

## I. INTRODUCTION

The rice yield of China has long been the highest in the world [1]. The cultivated area of rice in China is more than 450 million mu (1mu = 666.7m$^2$), and the yield of rice accounts for more than 30% of the total grain output, at present. The stable and high yield of rice is related to the development of the country and the standard of living. On one hand, timely and accurate rice yield estimation technology can grasp the global, national and regional yield dynamics, which is of great significance for guiding rice production scientifically and assisting the government to adjust agricultural policies timely and effectively. On the other hand, the development of rice yield estimation technology has given birth to an emerging economy of crop insurance based on yield estimation information [2]. Therefore, rice yield estimation provides an important information technology guarantee for national food regulation and security.

Rice yield estimation technology includes remote sensing technology, meteorological methods [3], field measurement and other forms. Due to many parameter requirements in field, it is not easy to measure, resulting in poor applicability of yield estimation in large areas. However, although meteorological methods are technically perfect, sampling and observation for large area yield estimation are still difficult and subject to the limitations of instruments [4]. With the development of technology, remote sensing yield estimation has the advantage of accurate and rapid production measurement over traditional meteorological and field measurement techniques. Remote sensing methods mainly include multispectral, hyperspectral and microwave. The multispectral and hyperspectral techniques of rice yield estimation, based on optical remote sensing, have been studied for a long time, and have already had reliable applications. For example, Crop Watch [5], a system built by the institute of remote sensing application of the Chinese Academy of Sciences, has served the global scale and has been operational for nearly 20 years. In addition, research teams such as Lu [6], Jiang *et al.* [7] and Huang *et al.* [8] have conducted many studies and achieved fruitful results, with the estimated yield accuracy above 80%. Rice is mainly distributed in the cloudy and rainy monsoon climate in south China and southeast Asia due to its climatic

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requirements. Optical remote sensing has two serious defects: 1) it is susceptible to cloud, rain and water vapor. For example, in places like Fujian and Guizhou, the probability of obtaining an optical image is less than 10% [9]. 2) insufficient ability to penetrate the target object. Therefore, the method of using multispectral and hyperspectral data to monitor rice yield over a large area has limitations.

SAR has many advantages over optical remote sensing technology [10]. Spaceborne Synthetic Aperture Radar (S-SAR), as an active remote sensing method, can record both the amplitude and phase information of signals, and has the ability to get the polarization scattering information of target [11]. SAR systems work in the band above centimeters and is not easily disturbed by clouds and rain, so it has all-day and almost all-weather observation capability and has extensive applications in crop monitoring and yield prediction [12].

S-SAR systems work at specific band ranges, such as L-band (1-2Ghz), S-band (2-4Ghz), C-band (4-8Ghz), X-band (8-12Ghz), Ku-band (12-18Ghz). Different operating frequencies have different characteristics in rice monitoring. Lower frequency (L-, S-, C-band) waves have more dominant, soil and other underlying ground features, backscatter contributions to the total backscatter compared to higher frequency (X-, Ku-, Ka-band), therefore, longer wavelengths have better penetration for rice [13]. On the other hand, different polarizations, including VV, HH, VH, HV, also have different characteristics for retrieving rice parameters. As Shao *et al.* [14] declared: 1) For rice monitoring, HH-, HV-polarization show that microwave backscatter is highly sensitive to the rice growth, while VV is sensitive during the early period after transplanting; 2) HH and VV can be used as relatively independent canopy data of rice measurement.

In this paper, the existing research status of rice yield estimation based on SAR was reviewed, the generation and development status of rice yield estimation technology based on S-SAR was introduced, and its future development was prospected.

## II. RICE YIELD ESTIMATION BASED ON S-SAR

According to the growing season, there are several types, like Summer–Autumn (SA), Autumn–Winter (AW), Winter–Spring (WS) [15]. For the rice growth cycle, there are several stages, including seeding, transplanting, tilling, jointing, heading and ripening. Different stage is with different microwave responding [14]. There are four main stages of rice growth cycle in as showed in Figure 1., which were the researchers mainly focused on.

In rice yield estimation studies, the two most important information sources are the planting area and the yield per unit. Rice yield is directly related to ear biomass [16], while total biomass and leaf area index (LAI) are the key variables to predict spike biomass [17]. Microwave can provide abundant plant geometry information [18], vegetation water content information [19], soil environment [20], biomass and planting area information [21]. Therefore, with SAR data inversion of rice ear biomass, it is feasible to achieve rice yield monitoring [22]–[26].

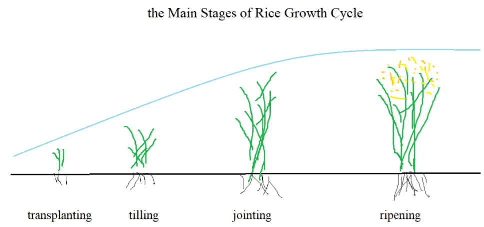


**FIGURE 1.** The four main stages of rice growth cycle for production estimation based on S-SAR.

After years of technical development, many breakthroughs have been made in rice yield estimation technology. With the continuous development of S-SAR technology, the rice yield estimation technology has developed in various stages, i.e., single polarization, multiple polarization and even full polarization, and the resolution has also been improved effectively. According to the inversion method, the estimation type mainly includes: 1) Inversion of plant parameters by $\sigma^0$ (backscattering coefficient); 2) Yield data fitted with $\sigma^0$ method [27]. According to the phenological period of the production estimating operation, the 1$^{st}$ method can be divided into i) Deriving the yield from the combination of inversion parameters and growth model and ii) direct inversion of rice panicle biomass method. According to the polarization characteristics and observation time, the method can be divided into single-polarized-multi-phase, single-polarization with single-phase, and multi-polarizations with single-phases, multi-polarizations with multi-phases and so on. This paper summarized the development of rice yield estimation technology in chronological order, and the polarization characteristics and observation timing of SAR data were taken as the main line.

### A. RICE YIELD ESTIMATION WITH SINGLE-POLARIZATION MULTI-PHASE

Research on SAR in rice estimation has been done since the 1980s. Toan *et al.* [28] used VANRAN-S to carry out the rice mapping experiment with an airborne SAR in X-band, indicating that VV and HH polarized microwaves have the ability to monitor rice. Comparatively speaking, the study of S-SAR in rice yield estimation was carried out relatively later. In 1994, Kurosu *et al.* [22], in the APCA, Akita, Japan, took agricultural university experimental field as the research object, used ERS - 1 (C-VV), analyzed relationship between the average $\sigma^0$ and the growth of rice, for the first time proposed to build the quantitative relationship between $\sigma^0$ and ground rice parameters in order to realize the possibility of monitoring rice based on S-SAR. In further study [23], by comparing the multi-temporal SAR data with the ground data, the experiment showed that the change of the mean backscatter coefficient was highly positively correlated with the height of rice and the biomass of the plant, however, the theoretical explanation for this correlation was not taken.

To solve this problem, Toan *et al.* [24], based on ERS-1 (C-VV) and Radarsat-1 (C-HH), respectively, established the empirical relationship between $\sigma^0$ and parameters, growth time, height and biomass of rice and the backscattering model of rice, realized rice mapping and parameter inversion. The height estimation error in the target area is less than 17cm, and the biomass estimation error is less than 315g/m2, which explains the correlation theoretically.

The weakness of the study lies in the failure to link radar data to rice yield. Ribbes and Toan [29] used ERS-1 and Radarsat-1 to retrieve the rice parameters, joined the ORYZA1 yield estimation model to realize the rice yield estimation. The validation accuracy reached 90% and 85% respectively, which fully demonstrated the research value and development potential of rice yield estimation by SAR. However, neither Le Toan nor Ribbes took into account factors such as meteorological conditions and farming techniques. In Central Vietnam, Mika and Risto [30] used ERS-2 and GIS for mapping and then established CROPWATN model for yield estimation based on meteorological data and soil information. The supervised classification algorithm (ISODATA), without prior knowledge, effectively reduces the difficulty of data processing. Compared with the statistical data, the accuracy is above 80%. The source of the error is mainly because the insufficient number of images obtained by ERS-2 and the low spatial resolution.

In summary, ERS-1/2 is used as a scientific investigation satellite, with low spatial and temporal resolutions, single incident angle, leading to limited observation ability. Radarsat-1 was the first commercially operated satellite providing sufficient data for rice yield estimation. Shao *et al*. [25] obtained the multi-temporal data of Radarsat-1 in Zhaoqing, China to classify rice, introduced digital elevation model (DEM) and estimated rice yield based on the empirical model established by local farming environment. At that time, due to the lack of accurate statistical data, precision verification could not be carried out, but once again, the potential of SAR based rice yield estimation was fully demonstrated.

Therefore, it can be seen that the monitoring of paddy fields based on S-SAR and the analysis of multi-temporal observation data can obtain higher precision rice yield. While almost monopolized commercial data can meet the observation demand, the research cost is too high, and the estimated yield of rice in a large area leads to too large data processing requirements [31]. Li *et al*. [32] used Radarsat-1 (SNB Model) to extract rice distribution information based on maximum likelihood classification, and established a rice yield estimation model based on time series information of rice. It was proved that the accuracy was above 96% in plain areas and about 80% in mountainous areas due to the influence of terrain. A high-resolution DEM was required to assist observation, which limits the model's application in hill or terrace fields.

Moreover, as with other crops, there were field differences in rice planting time and growth cycle affected by varying temperatures, which made classification and mapping more complicated at the regional scale. Although the researchers carried out the rice mapping based on the change index [33] and the time-phase change method [24], the problem of insufficient precision and fuzzy boundary was obvious. In the Nueva Ecija, Philippines, Chen and Mcnairn [26] introduced a DEM with 1:50,000 resolution scale in the study and obtained an average root-mean-square precision of 1-1.5 pixels. The change detection technique and neural network classification were combined to obtain the rice classification maps of cropping period and growing period of rice. In addition, Radarsat-1 data and ground observation data were used to train the neural network to realize the inversion of rice ear biomass. The estimation accuracy achieved 94%. Obviously, the neural network can overcome the spatial differences of rice parameters and expand its application. Unfortunately, the method only proved the feasibility of rice identification and yield estimation in wetland areas.

In summary, due to single-polarization data, ERS-1/2 and Radarsat-1 had the same limitations for rice yield estimation [31]. In order to identify rice using single-polarization images, it was often necessary to obtain the characteristics of time-phase changes through multi-phase image synthesis, which required at least three scenes in the rice growth cycle, with large data processing. At the same time, multi-scene registration was a difficult problem for a long time [34]. Currently, geocoding [2] technology was a relatively effective measure.

### B. RICE YIELD ESTIMATION WITH MULTI-POLARIZATION MULTI-PHASE

Through the observation and model simulation, Shao *et al.* [14] revealed, from a theoretical perspective, that multi-polarization SAR data has a superior potential in rice monitoring and yield estimation. ASAR, as a C-band S-SAR with multi-polarization, provides a favorable platform for the study of rice monitoring and yield estimation using multi-polarization data. Chen *et al.* [35] used multi-polarization radar to analyze the backscattering coefficient of several typical features such as towns, bridges and rice. The results demonstrated that ASAR has the capability of rice monitoring and yield estimation in areas with high cloud and rain in the south in terms of technology and application. Bouvet *et al.* [36] and Tan *et al.* [37] realized the identification and mapping of rice fields in the observation area, successively, based on HH/VV dual-polarization ENVISAT ASAR data based on single time phase, with mapping accuracy over 86%. The main idea was to set the thresholds of $\sigma^0$ (HH, VV and HH/VV) of urban areas, rice and other ground objects respectively, and then used the HH/VV to identify rice and map after removing the urban areas, which not only saved the experimental cost, but also reduces the workload of data processing.

Lam-Dao *et al.* [38] used this method to identify rice regions and then, based on the statistical model, fitted the HH/VV ratio of three-time phases to achieve rice yield estimation in the study region, proposing a statistical yield estimation model under the condition that the agrometeorological model could not be applied. However, how to determine the appropriate time to obtain the data was a difficulty. Shen *et al.,* [39] and Yang [9] also used HH/VV polarization ratio threshold to identify rice inversing the LAI based on water cloud model (WCM) [40] with the ASAR alternating polarization precision mode (APP). Based on the corresponding backscattering coefficients obtained by simulating the ORYZA2000 yield estimation model associated with LAI, the yield estimation was realized through parameter optimization of the assimilation strategy, which improved the universality of the yield estimation scheme with an accuracy of about 85%.

Thus, it can be seen that the ability of rice yield estimation can be ensured by multi-polarization and multi-temporal SAR data with a DEM. The main factors affecting the accuracy are as follows: 1) water and fertilizer conditions, meteorological and soil data are simplified to reduce the burden of data on the system; 2) the water cloud model is insensitive to LAI changes. In view of this problem, Yang *et al.* [41] established an improved water cloud model based on the spatial change characteristics in the rice growth cycle to realize LAI estimation, and RMSE values were between 0.23 and 0.52, fully reflecting the reliability of the model. However, the maximum spatial resolution of ASAR is more than 10 meters, while the maximum resolution of APP mode is 30 meters, which limits the further improvement of accuracy.

The launch of ALOS-2, RADARSAT-2, Cosmo-Skymed, TerraSAR-X, Sentinal-1/2 and other satellites with multi-mode, full polarization capability and higher resolution marked the entry of S-SAR into the era of full polarization, meter/submeter resolution, and provision of richer and more detailed data sources for rice yield monitoring. In addition, microwave at different wavelengths has different scattering responses to rice components [42], and researchers have explored different yield estimation schemes based on the characteristics of different bands. Like ASAR, RADARSAT-2 quad-pol SAR operates in C-band, but has higher spatial resolution and more polarization-polarization combinations. Fan *et al.* [43] monitored rice growth based on RADARSAT-2 quad-pol SAR data, analyzed the backscatter mechanism of rice by using Pauli decomposition, and demonstrated the reliability of RADARSAT-2 full-polarization data in rice yield estimation from a theoretical perspective.

Yang *et al.* [44] selected HH/VV combination as the best data source by comparing the ratio of polarization combinations, and adopted ratio change detection technology to achieve rice mapping in the study area, inputting parameters such as plant density, height and water content to establish a sub-model of ORYZA2000 to improve assimilation strategy to achieve rice yield estimation with an accuracy of 88.7%. Clauss *et al.,* [15] combined Sentinel time series data and random forest classification to realized production forecasting. Compared with previous studies, the yield estimation accuracy was improved. However, the results did not provide complete information on how the parameters change and how they affect the backscattering coefficients of rice. Moreover, the irrigation system in the study area was relatively developed, and the rice growth is not affected by water stress, so the spatial change of water content of the plant is not so significant. Therefore, the scheme still had a lot of uncertainty. On the other hand, Jia *et al.* [45] identified rice using multi-temporal RADARSAT-2 as data source based on supervised classification by support vector machine (SVM). The full-polarization ground scatterometer with the same parameters was used as the data source to establish the rice growth model and the physical scattering model based on Monte Carlo simulation. The rice parameters verified by the model and scattering data were paired with training neural network for rice mapping and biomass inversion, and the correlation coefficient was up to 0.989. The reliability of the model and the high resolution fully polarized data provides accurate data sources for further rice yield estimation. This scattering model is based on the scattering mechanism of microwave propagation in rice and reveals the interactions.

### C. RICE YIELD ESTIMATION WITH SINGLE-POLARIZATION SINGLE-PHASE

Compared with other crops, rice has a special growth habit. Most rice grows in south China and southeast Asian countries. In July and August every year, it is vulnerable to typhoons, rainstorms, high temperatures and other extreme weather [46]. In addition, the whole growth cycle may suffer from biological or non-biological stress, such as low temperature or dry head and neck, resulting in infertility [14]. In these cases, plant parameters such as total biomass and LAI cannot establish an effective relationship with spike biomass through the growth model. The key to overcome these technical shortcomings was to establish a direct quantitative relationship between $\sigma^0$ and spike biomass. As early as 2002, Shu *et al.* [11] used multi-frequency, full-polarization scatterometer to analyze the relationship between microwave backscattering coefficients at different frequencies and rice components. It was found that high frequency microwave (Ka-, Ku-, X-band) could detect seedling, revealing the potential of identifying rice planting areas in higher bands. It was also found that there was a high positive correlation between these high frequency microwave signals and spike weight and spike maturity, which provided a possibility for direct inversion of spike biomass. However, a key problem limiting the operational application of SAR in rice yield monitoring was the low resolution [47]. Compared with the plant body parameters of inversion of total biomass and LAI, inversion of rice ear biomass has a more stringent requirement on radar spatial resolution. However, high-resolution S-SAR of meter/submeter scale did not appear until around 2007.

In another study, Inoue *et al.* [48] combined RADARSAT-2 (C-band, VH polarization) and Cosmo-Skymed (X-band, VV polarization) radars with rice fresh weight, dry weight, water content, leaf area index and other parameters from ground measured, verified with an airborne CASI optical sensor, which the provided the evidence of direct inversion of ear biomass from higher band S-SAR, experimentally. Inoue and Sakaiya [17] discussed the correlation between Cosmo-Skymed data and ground rice parameters, revealing the potential of spaceborne high-resolution SAR to directly estimate rice yield at a regional scale.

On the other hand, Inoue *et al.* [47], based on the analysis of experimental data, proposed a ''water-point'' approach to extract the area based on the backscattering coefficient of calm water surface, to automatically classify and identify ground types, revealing the potential of S-SAR to directly extract rice planting area. Panicle grain biomass and panicle grain quantity were two important indexes related to yield, and panicle grain biomass is determined by filling degree, and panicle length and panicle diameter are important factors influencing panicle grain quantity. Inoue *et al.* [47], in the experiment, raised that VV polarization decreased with the increasing fullness during grain grouting, and the sensitivity of backscatter coefficient to panicle grain biomass was expounded from the experimental perspective.

From a theoretical perspective, Wang *et al.* [49] analyzed the scattering mechanism of rice based on the microwave scattering model of the paddy field, and realized that the value of HH polarization backscatter coefficient was greater than VV polarization, which gradually disappears with the increase of the size of the ear of rice. More significantly, the backscatter coefficient was almost linearly related to spike length, and there was almost no saturation state. This might be the first time that a close relationship between the geometric structure size of the ear of rice and the radar backscatter coefficient is established, in theory.

Based on the microwave scattering model of rice field, Liu *et al.* [50] analyzed the scattering mechanism and considered the influence of rice panicle layer, and obtained that in the c-band condition, the direct backscatter value of rice panicle dominated the total backscatter coefficient value of rice field. Combined with the experiment of Inoue *et al.* [42], the penetration depth of microwave is inversely correlated with frequency and incidence angle, Therefore, based on the microwave scattering model, quantitative analysis of the observation of classical scattering experiments in paddy field is the theoretical basis of rice yield estimation technology. The grouting period in the mature period is the key period that affects the yield and the yield measurement [50]. For large area yield measurement, the diversity of land use leads to the difference of farming among each paddy field [25], which further lead to the inconsistency of rice phenological period between fields. Thus, to determine the phenological period of each plot of rice, especially to identify the ripening period of the ear, is an important method to ensure the yield estimation accuracy at higher frequency. Compared with ENVISAT ASAR (Advanced Synthetic Aperture Radar on the European Space Agency's Envisat satellite), TerraSAR-X has a higher spatial and temporal resolution [51]. Lam-Dao *et al.*, [52] focused monitoring a total of five phases after seeding and chose three to five scene images and rice field measurement data to build statistical methods with linear regression fitting to acquire the production, compared with the official statistics, total output accuracy reached 95%, fully demonstrates the reliability of the high resolution SAR data. In another study, scenes of the middle and later period of rice growth were key data to ensure the accuracy of TerraSAR-X for yield estimation, effectively solving the previously difficult problem of determining the data acquisition time [38].

**TABLE 1. Several rice yield estimations based on single polarization 1S-SAR.**

| Time | Data | Band | Polarization | Categories | Accuracy |
|---|---|---|---|---|---|
| 1999 | ERS-1<br>RADARSAT-1 | C | VV/HH | (1)-i) | 90% /<br>85% |
| 2001 | RADARSAT-1 | C | HH | (2) | / |
| 2003 | RADARSAT-1<br>SNB | C | HH | (2) | 96%/80% |
| 2006 | RADARSAT-1 | C | HH | (2) | 94% |
| 2008 | ERS-2 | C | VV | (1)-i) | 80% |
| 2015 | Cosmo-Skymed<br>TerraSAR | X | HH | (1)-i) | 87% |

Rice yield estimation of single polarized S-SAR

### D. DIRECT YIELD ESTIMATION IN SINGLE PHASE WITH MULTI-POLARIZED S-SAR

Bernardis *et al.* [53] found that the different phenological periods of rice backscatter showed strong nonlinear changes. After combining the obtained probability density function, the most likely values were projected onto the model to determine the best estimated yield timing. Lopez-sanchez *et al.* [54] realized the estimation of rice phenological period based on polarization measurement.

In the production estimation research and application process, for higher frequency microwaves such as X-band, extreme weather such as heavy rain or thick clouds will affect the radar image, thus reducing the accuracy. For example, dense clouds appear as dark spots on the image, while heavy rain created bright spots on the image. On the other hand, since the microwave (L- and C-band) at low frequency had a higher ability to penetrate cloud and rain than higher frequencies (Ka-, Ku- and X-band) [11], it could not be directly established with spike weight, but the radar backscattering coefficient was closely related to the structure size of the spike [49].

In combination with the rice-field scattering mechanism of rice panicle layer [50], Zhang *et al.* [55] proposed a yield estimation scheme based on the rice canopy scattering model and genetic algorithm (RCSM-GA) in the maturity stage. Based on RCSM-GA, key parameters (spike length and spike number density) of rice were retrieved from RADARSAT-2 (HH&HV) data, and yield estimation was realized by combining field measured spike weight. Limitation of empirical statistical model was overcome and its universality was extended. The key factors to determine the accuracy are: 1) reliability of ground measurement parameters; 2) stability of the model; 3) the rationality of genetic algorithm parameter selection.

**TABLE 2. Several rice yield estimations based on multi-polarized S-SAR.**

| Time | Data | Band | Polarization | Categories | Accuracy |
|---|---|---|---|---|---|
| 2008 | ENVISAT ASAR APP | C | HH&VV | (1)-i) | 87% |
| 2009 | ENVISAT ASAR APP | C | HH&VV | (2) | 94%/87% |
| 2009 | ENVISAT ASAR APP | C | HH&VV | (1)-i) | 89% |
| 2011 | TerraSAR-X StripMap | X | HH&VV | (2) | 95% |
| 2012 | RADARSAT-2 fine quad-polarization | C | HH&VV &VH | (1)-i) | 88.7% |
| 2017 | RADARSAT-2 dual-pol | C | HH&HV | (1)-ii) | 85.6% |
| 2018 | Sentinel-1 | C | VV/VH | (2) | above97%/ inaccuracy (SA) |

Rice yield estimation of multi-polarized S-SAR

## III. CONCLUSION

In this paper we focus on summarizing the methods of rice yield forecasting based on S-SAR, including the developments and the methods. According to the methods, the estimations were divided into two categories (single-polarization and multi-polarized S-SAR). In addition, one of the categories was divided into two subclasses (multi-phase & single phase). Considering the polarization and the observation period, the estimation could be divided into four categories as displayed in this article.

Table 1 shows a comparison of result accuracy of different sensors based on various studies of rice yield estimation using single polarization S-SAR. It seems to be showed that HH polarization have better inversion ability for rice production forecasting than VV on single polarization. Table 2 shows a comparison of result accuracy of different sensors based on various studies of rice yield estimation using multi- polarization S-SAR. It is showed that method 2 may have the better yield estimation accuracy.

### A. SHORTCOMINGS

S-SAR technology has developed rapidly, but there are still many shortcomings in rice yield estimation:

1) the image speckle noise is relatively large and difficult to remove, which causes great interference to the extraction of rice information and will lead to the disappearance of rice information in severe cases [56].

2)Compared with the optical imaging, the backscattering characteristic of echo was the main remote sensing spectrum characteristic. The mechanism of side-looking imaging easily leads to shadow, foreshortening and lay-over of the image, which brings difficulties to the later analysis and processing of the data.

3)At present, most of the mainstream rice yield estimation methods were based on the empirical relationship between radar backscatter coefficient and rice parameters, while the difference of farming conditions and soil environment lead to the spatial distribution of rice parameters heterogeneous, and the rice parameters at the sampling point were not representative at the regional scale. Therefore, it was difficult to meet the demand of large area estimation. Even though the neural network has expanded its scope of application, there was still no theoretical explanation from the mechanism.

4)The correlation of multi-source information was helpful to improve the accuracy of rice yield estimation, but the massive information provided by multiple data sources greatly increases the amount of data processing, which has severe requirements on the computing capacity and stability of the system.

5)The high price of high-resolution SAR data in commercial operation leads to high research cost in rice yield estimation, which limits the wide application of SAR based rice yield estimation.

### B. FUTURE PROSPECTS

After years of development, SAR has gradually developed from single mode and single polarization to multi-mode, multi-polarization and even full polarization. It is expected to realize more accurate high-resolution quantitative measurement in the future, providing a more powerful tool for further accurate rice yield estimation. The rice yield inversion methods have also gone through empirical method to semi-empirical model and then to machine analysis method [57], which is gradually being applied. The universality of the estimation scheme will continue to improve. On the other hand, high resolution images and high precision DEM lead to the data processing volume continuously increasing. However, with the continuous application of genetic algorithm and other kinds of algorithms in rice yield estimation, the time complexity of future data processing will gradually decrease and the system operation will be more robust. The rice yield estimation technology based on S-SAR has the tendency of multi-modeling, big data, quantitative high resolution and model mechanism.

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