

雷达遥感农业应用综述(中文/English)

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摘 要: 雷达遥感具有全天时、全天候监测的能力,对植被具有一定的穿透能力,对植被散射体形状、结构、介电常数敏感;这些特性使得其在农业应用中极具潜力。该文首先介绍了雷达遥感在农业中的应用领域,概略总结了目前在农作物识别与分类、农田土壤水分反演、农作物长势监测等多个领域研究的综述文献;然后分别阐述了雷达散射计和各类SAR特征(包括:SAR后向散射特征、极化特征、干涉特征、层析特征)在农业各领域中应用的现状和取得的研究成果,最后结合农业应用需求和SAR技术发展总结了目前研究中存在的问题和原因,并对未来的发展进行了展望。

关键词: 雷达遥感;农业;后向散射特征;极化特征;干涉特征;层析特征

中图分类号: TN957.52

文献标识码: A

文章编号: 2095-283X(2020)03-0444-18

DOI: 10.12000/JR20051

引用格式: 张王菲,陈尔学,李增元,等. 雷达遥感农业应用综述[J]. 雷达学报, 2020, 9(3): 444-461. doi: 10.12000/JR20051.

Reference format: ZHANG Wangfei, CHEN Erxue, LI Zengyuan, *et al.* Review of applications of radar remote sensing in agriculture[J]. *Journal of Radars*, 2020, 9(3): 444-461. doi: 10.12000/JR20051.

Review of Applications of Radar Remote Sensing in Agriculture (in English)

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Abstract: Active radar remote sensing technology, with its capability of acquiring all-weather data, has great potential for agricultural monitoring. This technology can penetrate vegetation cover more deeply than optical sensors and has sensitivity to the shapes, structures, and dielectric constants of vegetation scatterers. In this paper, we discuss the applications of radar remote sensing in crop identification, cropland soil moisture inversion, crop growth parameter inversion, crop phenology retrieval, agricultural disaster monitoring, and crop yield estimation. We review several specific papers focusing these fields, and then describe the results obtained using information extracted from radar scatterometers and Synthetic Aperture Radar (SAR). Extracted SAR data include characterizations of backscattering, polarimetry, interferometry, and tomography. Lastly, we summarize the problems faced by radar applications in agriculture and consider the future trend of these applications.

Key words: Radar remote sensing; Agriculture; Backscattering characterizations; Polarimetric characterizations; Interferometric characterizations; Tomography characterizations

收稿日期: 2020-04-30; 改回日期: 2020-06-15; 网络出版: 2020-06-28

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基金项目: 国家自然科学基金(31860240), 国家重点研发计划(2017YFB0502700)

Foundation Items: The National Natural Science Foundation of China (31860240), The National Key R & D Program of China (2017YFB0502700)

责任编辑: 廖明生 Corresponding Editor: LIAO Mingsheng

1 引言

1.1 研究背景

雷达是微波遥感应用中的主要传感器。微波遥感的优势主要包括3个方面：(1) 微波具有穿透云层甚至穿透雨区的能力；(2) 微波比光波能更深地穿透植被；(3) 微波与光学遥感得到的信息是不同的，它可以得到研究对象面或体的几何特性和介电特性^[1]。由于雷达遥感全天时、全天候监测的能力，在对植被散射体形状、结构、介电常数敏感的同时具有一定的穿透能力，因此在农业监测中极具潜力。

雷达遥感目前在农业中的应用主要包括农作物分类与识别、农田参数(含水量和地表粗糙度)反演、农作物长势参数反演(生物量，叶面积指数(Leaf Area Index, LAI)和高度)、农作物物候期划分、农作物灾害监测和农作物估产等。

农作物分类与识别是农情监测技术体系的初始和关键环节。精准识别各种农作物类型可实现对农作物种植面积、结构及空间分布的准确估计，并为农作物估产模型提供关键输入参数^[2]。各种农作物具有不同的冠层结构、几何特性和介电常数等，从而导致在不同频率和极化的合成孔径雷达(Synthetic Aperture Radar, SAR)影像中表现为不同的特征，这是采用雷达遥感进行农作物分类和识别的理论基础。

农田参数反演中利用雷达数据进行土壤含水量反演是雷达遥感最经典的应用之一。但是在农田土壤含水量反演中，特别是在裸土含水量反演中，受到地表粗糙度的影响较大，另外，地表粗糙度也是农学、土壤学、地质学和气候学中的重要参数，因此地表粗糙度的反演也逐渐发展为一个独立的分支^[3]。此外，在有农作物覆盖的地区，农田土壤含水量反演中还要考虑农作物植被层的影响。将植被冠层、土壤粗糙度的影响从雷达信号中分离后，雷达后向散射系数和土壤含水量之间具有较好的相关性，通常通过建立雷达后向散射系数与土壤体积含水量之间的关系模型就可实现农田土壤含水量的估测^[2-4]。

农作物长势即农作物生长状况和趋势，直接影响农作物的产量和品质^[5]。农作物长势参数主要包括生物量、LAI高度和密度等。长势参数通常是农作物生长状况的有效表征，因此农作物的长势监测通常通过长势参数的反演来实现。雷达的后向散射参数、极化特征参数和干涉特征参数常被用于农作物生物量、LAI和高度的反演。

农作物物候信息是农业生态系统的重要特征之

一，是农业生产、田间管理、计划决策等的重要依据。农作物物候期划分主要是区分农作物形态发生显著变化所对应的时间段，即从出苗到收获所经历的生长时间周期^[6-8]。由于极化SAR特征对农作物结构、形态变化敏感，近年来被广泛应用于农作物物候期的划分。

农作物灾害类型较多，包括洪涝、干旱、病虫害、倒伏等。雷达遥感在农作物灾害中的应用目前开展较少，多集中在倒伏的监测，特别是对垂直结构明显的农作物倒伏的监测具有较大潜力，这主要是利用了极化特征对农作物结构变化敏感的特点^[9]。

农作物精确估产是农业遥感监测的最终目标。目前农作物估产可通过农作物生长模型和遥感估测两种手段进行。前者通过数学建模方法在单点尺度模拟农作物生长，可以实现高精度的农作物单点估产；后者可获取农作物区域尺度上的面状特征，两者优势互补，集成应用于农作物估产可以提高估产的准确性和机理化^[8,9]。雷达遥感目前应用于农作物估产也是通过遥感数据与农作物生长模型的同化来实现，但是相关的研究也仅在近期展开^[3,8]。

1.2 现有研究综述概况

随着雷达遥感技术在农业应用研究中的深入，目前不少研究者从多个应用领域对其研究情况进行了文献综述。王迪等人^[2]综述了SAR技术在农作物分类与识别中的研究进展，总结得出：目前用于农作物识别与分类的SAR特征包括单波段、单极化特征、多极化特征和多波段特征；分类方法包括非机理性的基于像元统计特征的分类方法、利用极化分解理论分析和农作物散射特征发展的机理性分类算法。他们同时指出目前的识别分类精度还较低，多数识别精度不足85%，其可能原因是分类算法的机理性研究不足。施建成等人^[4]综述了土壤水分反演中用到的雷达数据源、各数据源的局限、目前采用的算法及不足等；刘健等人^[10]则综述了土壤水分反演中粗糙度、植被覆盖等的影响及相应的解决措施，并指出现有反演方法的准确性和普适性有待进一步提高，融合不同观测模式(多波段、多极化、多角度)的SAR数据是未来的发展趋势。Liu等人^[3]和McNairn等人^[11]综述了基于SAR技术的农作物长势监测，指出目前用于农作物长势监测的长势参数包括生物量、LAI和高度，使用的SAR特征包括后向散射特征、极化特征和干涉特征。李平湘等人^[9]对基于SAR技术的农作物物候期监测进行了简单的综述，指出目前主要的方法包括两大类，即利用分类和时序动态跟踪两种方法。他们还总结得出目前SAR技术在农业灾害监测中的研究还开展较少，已

有研究主要集中在“农作物倒伏”方面。黄健熙等人^[12,13]综述了遥感数据与农作物生长模型同化在农作物估产中的应用,指出SAR遥感数据与农作物生长模型同化在农作物估产中的潜力,但目前应用较少,是未来农作物估产主要的发展方向之一。

现有的研究综述从多个方面说明了雷达遥感在农业应用中的优势和不足,对推动雷达遥感技术在农业中的应用有积极的意义。然而,随着SAR技术的发展及应用需求的推动,SAR数据获取方式由单频率、单极化、单角度等发展到多频率、多极化、多角度和多时相等综合获取方式。原有的针对单一观测和几个观测的简单组合已经不适用于描述观测对象的复杂散射特征和提高定量遥感的精度,SAR观测方式的改变使得农作物的散射机理及其在SAR图像中的表征呈现出复杂性,不仅影响了采用SAR技术对农作物的认知和理解,也影响了传统估测方法在联合观测维度下SAR技术在农业应用中的适用性。为了适应SAR多维度观测技术的需求,需要从不同SAR数据获取方式出发,系统地梳理农业应用中SAR参数的提取方式及其对农作物各相关参数的响应情况^[14]。已有的研究中,初期用于农业相关监测的传感器主要是雷达散射计,近期使用的传感器则多为SAR,目前的综述研究多集中于SAR应用的研究。然而初期基于雷达散射计的研究是后续SAR技术应用的实验基础,其研究结果对微波遥感理论的验证也是SAR技术进一步发展的理论保障,因此有必要对其研究结果进行全面的梳理和总结。此外,已有的综述文献中部分发表较早,近年来新的研究成果并未加入,特别是对干涉、极化干涉SAR技术、层析SAR技术在农业中应用的文献未作深入总结。鉴于此本文首先对雷达散射计在农业应用中的现状进行综述、总结;然后以不同的SAR观测技术为基础,综述各类SAR技术在农业各领域中的应用现状;以期能够较全面的梳理目前SAR技术在整个农业系统应用中的优势和不足,并为将来更深入的应用提出可能的方向和思路。

2 雷达散射计农业应用

雷达散射计在农业应用中的研究多集中在农田土壤水分的反演。初期的研究也探索了其在植被冠层结构、农作物制图、农作物长势监测和农作物识别分类中的应用,但相比土壤水分的研究,这些方面的研究成果较少。采用雷达散射计的研究成果按照遥感平台,可以分为地基散射计、机载散射计和星载散射计,下面我们将以遥感平台为基础,总结目前的研究进展。

2.1 地基雷达散射计

雷达散射计能够获取目标的散射截面观测量,可以用于深入理解微波和自然目标相互作用的机理。散射计通过发射系列脉冲并测量其回波,然后将回波特性定量化来获得目标的散射截面测量结果。散射计的荷载平台包括星载、机载和地面平台,其中地面平台主要搭载在高塔上或者卡车上,又称为地基散射计。散射计量测的目标散射截面除了受到目标自身特性的影响外,散射计的频率、入射角、极化方式均会影响其测量结果^[15]。

表1总结了使用地基雷达散射计开展的研究,同时整理了其研究结论。由表1可知,基于地基散射计进行土壤水分反演方面的研究最早开始于60年代末70年代初,前期的研究目的主要是为星载散射计、星载SAR在相关研究中的优选参数设置提供理论和实验支撑。堪萨斯大学使用主被动辐射计(Microwave Active and Passive Spectrometer, MAPS)或主动散射计(Microwave Active Spectrometer, MAS)研究了频率范围为1~18 GHz之间,入射角范围在0°~80°之间各种极化组合下,后向散射系数对土壤水分变化的反映情况。研究结果表明:采用后向散射系数反演土壤水分受到频率、极化、入射角、土壤粗糙度和地表覆盖植被的影响;土壤粗糙度的影响可以通过选择合适的频率、入射角来剔除或降低;低频低入射角更适合土壤水分反演。极化特征对农作物结构变化敏感,各极化与高频、大入射角特征组合更容易区分不同的作物类型^[16-23]。荷兰的微波植被观察项目(Radar Observation of VEgetation, ROVE)主要研究了X-波段各极化后向散射在不同入射角变化下对农作物参数的响应情况,研究表明:农作物的地表覆盖率达到一定程度时,后向散射系数会出现饱和现象;多频率观测可以提高农作物生长参数的估测精度,研究结果同时肯定了大入射角更适合植被监测^[24-27]。日本学者Inoue等人^[28]基于Ka-, Ku-, X-, C-和L-波段地基散射计数据对农作物长势监测的研究则指出C-波段适合LAI反演,而L-波段则适合生物量估测。加拿大遥感中心的相关研究指出HV极化对农作物类型识别、农作物残茬识别有较好的识别效果;同时指出后向散射对农田区每日含水量动态变化响应明显,但其相关性受到频率、田间农作物生长阶段的影响^[29-33]。我国研究者主要探索了土壤水分在X-, C-波段不同极化、不同入射角的后向散射变化及其影响因子,研究表明垄向对与其平行的极化方式的后向散射有显著影响;土壤含水量反演中,粗糙度的影响可以通过选择特定入射角的数据来剔除^[34-37]。

表 1 地基雷达散射计研究现状总结
Tab. 1 Summary of studies using ground-based scatterometers

研究团队	散射计相关参数描述		应用类型(对象)	研究结论	参考 文献
	名称	参数描述			
MAPS		双极化(HH+VV); 入射角可在0°~70° 之间变化, 频率4~ 8 GHz	土壤水分	后向散射对于土壤水分的敏感性: HH>VV; 后向散射对土壤水分的敏感性受到土壤表面粗糙度的影响明显, 土壤表面的粗糙度可以通过频率和入射角的变化来表征, 因此土壤水分反演受到频率和入射角的影响明显; 当频率在4~8 GHz, 入射角在5°~15°时, HH极化的后向散射几乎不受地表植被的影响, 仅反映土壤水分的变化。	[16-18]
		全极化(HH+VV+HV+ VH); 入射角可在 0°~80°之间变化, 频 率4~8GHz	农作物分类制图 (农作物包括: 玉米、高粱、 大豆和苜蓿)	极化特征对农作物结构变化敏感; 农田的垄向对极化散射特征影响明显, 其影响具有农作物类型依赖性; 对于农作物结构变化的敏感性: VV>HH; 农作物密度和入射角变化均会影响不同频率微波的后向散射强度; 大入射角(30°~65°)和高频段组合可以最有效的区分不同农作物类型。	[18]
堪萨斯大学Ulaby 等团队		双极化(HH+VV); 入射角可在7°~15°之 间变化, 频率2~ 8 GHz	裸土覆盖区土 壤水分	土壤粗糙度会影响裸土覆盖区土壤水分的反演; 通过优化散射计的系统参数可以降低土壤粗糙度的影响, 推荐的组合是频率为4 GHz, 入射角在7°~15°, 极化方式为HH或VV。该参数在频率4~8 GHz之间的植被覆盖区的土壤水分反演中也适用, 后向散射与土壤水分的最高相关性获得时频率为4.7GHz, 入射角为10°。	[18,20]
	MAS	三极化(HH+VV+ HV); 入射角可在0°~ 80°之间变化, 频率 1~8 GHz	土壤水分、地 表粗糙度、土 壤结构	对于裸土覆盖区的土壤水分, 结论与文献[20]相似, 地表粗糙度的影响在频率为5 GHz, 入射角在7°~17°时影响最小; 在有农作物覆盖区的土壤水分反演中, 后向散射与土壤水分的相关性在频率4.25 GHz, 入射角为10°, 极化为HH时最高, r=0.92; 后向散射系数对土壤水分的估测力依赖于土壤水分在田间含水量中所占的比例, 当其比例低于50%时, 估测力低, 在50%~150%之间时, 估测力高。	[21-23]
荷兰 ROVE 项目	FM/CW	X-(10 GHz)、Q(35 GHz); 角度15°~ 80°, 极化: VV, HH, VH, HV	农作物观测、 土壤水分	除了与文献[18]相似的结论, 还得出: 采用VV的多频数据可以获得最好的农作物识别效果; 入射角在30°~65°时可以将土壤水分在农作物识别中的影响降低到最小; 低频小入射角数据可以获得更好的土壤水分反演结果。	[19]
				农作物的后向散射系数受到极化方式、观测角度等影响明显; 这种成像几何的影响具有农作物类型依赖性: 例如入射角变化对甜菜影响不明显, 但是对马铃薯的影响可达到-5 dB; 此外当地表农作物冠层的覆盖率达到80%时, 后向散射系数变化呈现饱和; X-波段可用于农作物的分类识别; 多频数据联合观测有助于提高农作物冠层生物量、冠层含水量、覆盖度和农作物高度估测的精度; 增大观测入射角可以提高冠层含水量的估测精度。	[24-28]
加拿大 CCRS相 关项目	FM/CW	L-, C-, Ku(1.5, 5.2, 12.8 GHz); 全极 化; 角度0°~85°	农作物识别与 分类、土壤水分、 农作物冠层水 分、农作物残余	通过方差系数分析得出Ku-波段、HV极化、入射角范围在30°~60°, 农作物生长29~30周时, 可以得到最优的农作物识别效果; 在农作物快速生长阶段, 后向散射与每日冠层含水量变化相关性较高, 农作物凋谢时, 后向散射与每日土壤水分变化相关性较高, 相关性同时受到频率的影响; HV对农田农作物残余变化敏感, 并且不易受到观测方向或垄向的影响。	[29-33]
	地基微波散射计 (FM /CW)	C-; HH和VV	土壤水分土壤 粗糙度	垄向使得与其平行的极化方式的后向散射系数增强; 反演测得的粗糙度不同于光学方法得到的粗糙度。	[34,35]
中国	微波散射计 (FM /CW)	X-(9.375 GHz), 角 度为0°~48°, 步进间 隔为6°; 全极化	土壤水分	X-波段HH极化在6°时对裸土含水量灵敏度最高, 有植被覆盖的土壤水分反演中, X-波段比C-波段差; 含水量一定时, 后向散射系数随入射角增大而减小, 变化率随粗糙度增加而减小; 随着频率的增加, 与粗糙度无关的入射角增大, 频率为1.1 GHz时, 入射角为7°, 7.5 GHz时为10°。	[34,36,37]
其他	ComRAD	双极化, 1.4 GHz辐 射计; 全极化 1.25 GHz	农作物含水量 (VWC)	在L-波段采用HH、VV、极化差系数(MPDI)、雷达植被指数(RVI)进行VWC反演中, HV效果最好。	[38-40]
	UF-LARS	L-(1.25 GHz), 全极 化, 入射角40°	土壤水分, 农 作物长势	采样时间间隔降低可以显著提高反演的土壤水分的精度, VV极化后向散射对农作物的垂直结构变化更敏感; 在植被体散射为主导机制的土壤水分反演中, 表面较光滑、土壤较干燥时, 线性关系反演结果不确定较大。	[41,42]

另外一些其它的实验也取得了与以上研究类似的结论^[38-42]。

2.2 机载和星载雷达散射计

尽管地基散射计操作方便、成本较低,但是由于平台较低,观测结果受到几何关系影响较大,并且观测范围受到很大限制,因此采用机载平台可以扩大观测范围,提高观测效率。机载平台主要作为地面平台的补充,为星载雷达传感器参数的设置提供理论和实验支持。在荷兰ROVE项目中即包括侧视机载雷达数据,Kurl等人^[42]使用该数据研究了农作物整个生长期X-波段后向散射系数的变化,发现动态变化范围为3~15 dB。大量的研究成果基于欧洲的1~18 GHz DUTSCAT和C-/X-波段的ERASME机载散射计^[43,44]。Bouman等人^[45]和Ferrazzoli等人^[46]采用DUTSCAT的多频数据肯定了文献^[27]的研究结果,同时指出X-,Ku-波段适合农作物分类,而L-波段更适合土壤水分反演;Benallegue等人^[47]使用ERASME的多频、多角度数据分析了土壤水分反演的可行性,得出的结论与文献^[16-23]相近。

根据地基和机载的实验结果,星载散射计主要的工作波段在C-(5.3 GHz)和Ku-(13.5 GHz)波段。C-波段波长较长,受云雨因素影响较小;Ku-波段频率高,对目标特征变化更敏感。表2列举了到目前为止主要的星载散射计的主要信息^[48-51]。星载散射计数据在农业中主要应用于土壤水分反演和农作物参数反演。WoodHouse等人^[52,53]采用ERS-1 AMI散射计数据反演了植被覆盖度、植被覆盖下的土壤水分、植被的季节变化等,研究结果表明土壤水分反演结果受到植被覆盖的影响,因此具有地域依赖性。Frison等人^[54]则发现植被的季节变化观测

结果会受到空气和地表温度的影响。Frolking等人^[55]采用QuickSCAT SeaWinds在美国27个地点监测了多种植被的物候期,并与MODIS LAI数据进行了对比,发现两者的结果基本一致,但是采用后向散射特征监测的各物候期总早于MODIS LAI的结果。Lu等人^[56]在中国22个地点采用相同数据的研究结果与该研究的结论一致。Wen等人^[57]也采用ERS-1 AMI数据反演了西藏地区的土壤水分,散射计估测结果与地面调查的0~4 cm表层土壤水分的相关性达到0.78。多个学者基于星载散射计的数据,完成了全球范围土壤水分制图^[58,59],也有学者指出全球性土壤水分制图应该考虑地表植被动态变化的影响^[60]。Kim等人^[61,62]采用蒙特卡洛模拟的方法,研究了适用于16种植被和裸土表面的前向散射模型,并将其用于土壤介电常数、粗糙度、植被含水量等参数的模拟,以期为NASA的SMAP数据提供分析方法。Naemi等人^[63]和Wagner等人^[64]则基于这些数据进行了反演算法、模型的优化。

早期围绕地基和机载散射计数据开展的研究阐述了采用后向散射特征进行土壤水分反演和农作物分类的可行性,星载散射计的应用进一步优化了早期的反演方法,更推动了星载散射计在土壤水分和植被参数反演方面的应用。随着成像雷达、特别是SAR技术发展,SAR技术被广泛应用到农业各领域的应用中,由于散射计观测的灵活性、低成本、快速重复观测能力等使得其在农业应用中仍然是SAR数据应用的一个重要补充。

3 SAR农业应用

相比散射计,SAR可以提供图像特征和除后向散射特征以外的其它观测量,近些年来被广泛应用

表 2 星载散射计信息

Tab. 2 Major space-borne radar scatterometry and their basic information

卫星	传感器	波段	入射角	极化	服役时间	国家
Seasat	SASS	Ku	25°~55°	HH, VV	1978-6—1978-10	美国
ERS-1	AMI	C	18°~59°	VV	1991-6—2000-3	欧空局
ERS-2	AMI	C	18°~59°	VV	1995-4—	欧空局
ADEOS-1	NSCAT	Ku	18°~63°	HH, VV	1996-8—1997-6	美国
QuickSCAT	SeaWinds	Ku	46°, 54°	HH, VV	1999-7—	美国
ADEOS-2	NSCAT	Ku	46°, 54°	HH, VV	2002-12—2003-8	美国
SZ-4	CN/SCAT	Ku	37°	HH, VV	2002-12—	中国
MetOp-1	ASCAT	C	25°~65°	VV	2006-10—	欧空局
OceanSat-1	OSCAT-1	Ku	50°, 57°	HH, VV	2009—	印度
HY-2A	HY-2A	Ku		HH, VV	2010-8—	中国
OceanSat-2	OSCAT-2	Ku	50°, 57°	HH, VV	2016—	印度
	SMAP	L-			2015-1—2015-7	美国

于农业各类监测中。综合目前SAR技术可以提供的特征，应用于农业中的特征可划分为四类：后向散射特征、极化特征、干涉特征和层析特征，其中层析特征是干涉或极化干涉特征在垂直空间中的进一步拓展。

3.1 SAR后向散射特征

由于初期(20世纪80年代末—2002年)的SAR数据仅可获得单频率、单极化的影像，因此其可应用的特征仅为后向散射特征。SAR后向散射特征在农业中的应用基本上是基于散射计获得的后向散射特征在农业应用中的进一步验证和深入，因此初期的研究多是对基于散射计数据研究结果的验证，使用的方法也多基于散射计研究的方法和模型^[65-70]。在采用单波段、单极化后向散射特征进行农作物的识别时，由于水稻下垫面(水面)独特的散射机制，使得与其它农作物的区别明显，因此基于后向散射系数的农作物识别多以水稻为研究对象。为了提高识别的精度，基于后向散射的时相特征被用于农作物识别、长势监测及估产中。利用这些特征进行水稻识别时，分类精度可以达到80%，91%和98%^[65]。然而，这些研究的区域多位于空间异质性比较低的地区，对于地块破碎、种植结构比较复杂的区域，分类识别的效果明显降低^[65,66]。土壤水分和农作物长势参数反演中多通过建立后向散射与反演参数之间的模型来实现，这些模型包括经验模型、半经验模型和机理模型。经验模型通常通过实验观察数据来建立，因此对实验数据获取的条件敏感，例如气象条件、成像几何、农作物情况、农作物类型、物候特征、土壤水分状态等。这些敏感特征会造成反演结果的不确定性，同时降低模型的适用性。由于经验模型的这些局限，一些研究开始发展半经验模型和机理模型。在基于后向散射的裸土水分反演中，采用较多的模型为积分方程模型(Integral Equation Model, IEM)、高级积分方程模型(Advanced Integral Equation Model, AIEM)以及基于这两者改进的相关模型。常用的算法包括变化检测法、回归分析法、基于模型的人工神经网络法等^[67]。用于植被参数反演的具有代表性的半经验模型为水云模型(Water Cloud Model, WCM)^[68]，机理模型为密歇根植被散射模型(MIchigan MIcrowave Canopy Scattering, MIMICS)^[69]。这两类模型也常被用于植被覆盖区土壤水分反演时降低植被的影响。为了更精确的提高这两类模型在生长参数反演中的精度，不少学者通过引入更多的特征对其进行了改进^[70-75]，文献^[3]综述了这两个模型在农业中的详细应用现状。目前采用雷达数据进行农作物估产中使

用的特征多为后向散射系数。农作物估产方式通过两类方法实现：一是直接采用后向散射系数进行农作物估产；二是通过基于后向散射的生长参数估测结果与农作物生长模型同化进行农作物估产。直接采用后向散射系数进行产量估测通常是建立后向散射系数与产量的关系模型，然后反演产量，属于经验模型，尽管在特定区域可以获得较好的估测精度，但是受到经验估测模型自身缺陷的影响，无法大面积推广^[76,77]。基于SAR遥感信息与农作物生长模型同化的研究于近年来才刚刚展开，目前用于同化的信息主要包括基于SAR后向散射特征反演的生物量和LAI^[78,79]。

3.2 SAR极化特征

全极化SAR数据起源于20世纪90年代初，记录了地物HH, HV, VH和VV, 4种极化状态的散射振幅和相位特征，极化特征的提取通常包括极化合成和极化分解技术。采用极化合成技术可以计算任意一种极化状态的后向散射回波，进而提取地物更多的特征；而通过极化分解技术也可以将地物的特征进一步细化，以此增强地物的探测能力。由于极化特征不仅具有后向散射对农作物生理特征敏感的特征，同时具有对农作物散射方向、形状敏感的极化特征，在农业的各项研究领域均具有极大的潜力，也是目前农业应用中使用最广泛、研究最深入的SAR特征。表3列出了目前极化特征在农业主要领域中的应用现状。

从表3可知，极化特征已应用到农业中的诸多方面。农作物识别和分类是极化特征在农业中应用最早的领域。初期的研究多通过增加不同极化的后向散射特征来提高农作物的分类精度，研究发现随着极化特征的加入，可以将仅采用单一极化特征的农作物分类精度有效提高，部分地区某些农作物的分类精度可提高37%^[91,92]。随着多种极化分解方法的提出，不同学者的研究表明：引入不同的极化分解参数，可以有效提高分类的精度，这些分类结果的精度范围在70%~96%之间变化。分类的对象包括农作物中的玉米、大豆、小麦、水稻等；也包括农作物与森林、裸土、建筑物等^[93-95]。文献^[65]也详细总结了使用这些特征进行分类的方法。

在农田土壤水分反演中，极化特征的加入有效降低了基于后向散射特征反演土壤水分中的不确定性^[96,97]。不少学者提出了多极化数据反演算法来提高土壤水分的反演精度^[98-100]，加入极化特征后土壤体积分含水量的反演均方根误差可以低于4%^[98]。极化特征对土壤粗糙度的敏感性最早也通过极化合成参数对其的响应得到证实，研究表明圆极化相关

表 3 极化特征在农业中的应用现状

Tab. 3 Summary of studies using polarimetric characterization

应用类型	SAR参数描述	结果	参考文献
农作物分类与识别	Pauli分解参数, Stokes参数, 基于特征值、特征向量分解参数, Freeman-Durden, Yamaguchi分解参数, Span-Pauli分解参数, $H-A-\alpha$ 分解参数, Cloude分解参数	(1)加入极化特征, 可以有效提高分类精度; (2)对于不同农作物的可区分性差异明显; (3)在极化特征中加入时相特征可以有效提高农作物分类精度; (4)加入极化分解特征比仅采用简单的线性极化组合的分类精度高; (5)简缩极化特征的分类结果几乎可以达到全极化特征分类的精度水平。	[3,65,66]
农田参数反演(土壤水分/地表粗糙度)	(1)引入去极化率、同极化相关系数、相干性参数、散射熵和散射角等参数分析土壤水分和后向散射系数的变化关系; (2)采用极化分解的参数, 主要包括Freeman-Durden和特征值分解的参数。	(1)利用多极化特征可降低采用单极化特征反演土壤水分中的不确定性, 提高反演精度; (2)利用极化分解的参数替代后向散射系数可以提高反演精度; (3)引入极化参数后, 反演结果受到农作物物候期和农作物类型的影响。	[3,67]
农作物长势参数反演	极化合成和极化分解参数; 基于极化合成及分解参数发展的参数; 如各种雷达植被指数、基准高度参数等。	(1)生长参数包括LAI、生物量和农作物高度; (2)X-、C-波段对LAI变化敏感, (3)反演结果受到农作物物候期和农作物类型的影响; (4)多种极化合成及分解的参数可以获得更高的农作物生长参数反演精度(目前已经用于农作物长势参数反演的参数约为30个)。	[80-83]
农作物物候期划分	Cloude-Pottier分解参数、极化比、极化差值比、极化合成参数(极化度)、简缩极化后向散射系数及极化分解参数、Stokes参数	(1)主要采用时间序列数据进行物候期的划分或监测; (2)方法包括利用分类和时相动态跟踪两类方法; (3)用于监测的数据包括X-和C-波段。	[9,84-88]
农作物灾害监测	极化指数(HH/VV, HH/HV, 表面散射/Span, 二次散射/Span)	(1)不同极化特征对倒伏现象响应差异明显; (2)极化熵、极化指数均可以反映倒伏现象; (3)倒伏发生伴随着散射机制的明显变化, 因此可以通过极化特征表征。	[89,90]

参数对土壤粗糙度最为敏感^[101]。随后, 极化分解参数被应用于土壤水分反演中土壤粗糙度影响的剔除, 并在此基础上提出了X-Bragg模型来改进传统土壤水分反演模型——小扰动模型(Small Perturbation Method, SPM)无法表征交叉极化、去极化特征的弊端^[102,103]。随着全极化数据的丰富, 一些研究开始探索更多可以表征土壤粗糙度的特征参数^[104,105]。

极化参数在农作物长势参数中的反演也是目前研究的热点之一, 近年来涌现出不少研究成果。加拿大农业与食品学会的研究团队针对多种农作物, 以Radarsat数据为主要数据源, 开展了多个长势参数的反演及农作物估产研究^[106-108]。国内中科院邵芸团队^[109,110]也采用全极化和简缩极化数据, 以水稻为主要研究对象, 研究了极化特征在农作物长势监测及估产中的应用。Jiao等人^[106]和McNairn等人^[107]采用极化参数(HV强度、基准高度、极化分解的体散射分量等)证实了SAR极化特征对LAI的敏感性, 并通过改进传统的水云模型, 克服了采用后向散射反演LAI的低饱和点的局限, 同时也论证了LAI可以作为农作物估产有效指标。Wiseman等人^[108]则全面分析了C-波段极化参数对玉米、大豆、油菜、春小麦的干生物量的响应情况, 指明各极化参数对农作物的敏感性受到农作物类型和生长物候期的影响, 也表明极化特征在农作物物候期监测中的潜力。Zhang等人^[111]通过提取27个简缩极化参数表明了不同极化参数在农作物生物量、LAI和株高中

反演的潜力。然而, 以上研究多采用极化参数与农作物长势参数直接建立关系来实现反演, 地域依赖性强, 一些研究利用了半经验模型折衷的优势, 将极化特征用于WCM模型来提高反演结果的精度和适用性^[112,113]。SAR技术应用于物候期的识别多数采用了极化特征对农作物生长期结构变化敏感的优势, 首先通过覆盖物候期的SAR极化影像提取极化特征; 然后分析农作物在整个生长过程中各极化参数的变化特征, 进而选取合适的极化参数进行各个物候期的划分, 初期物候期划分的方法多采用影像分类的方法^[84,85]。为了克服该方法中经验阈值鲁棒性低的问题, 一些研究者发展了动态建模的方法, 如Kalman滤波和粒子滤波等方法^[114,115]。考虑到监测物候期中时间序列影像缺失对物候期反演结果的影响问题, 一些研究通过采用替代参数和滤波方法相结合来弥补^[86-88]。

杨浩等人^[90]率先将极化特征用于小麦倒伏灾害的识别, 研究发现小麦倒伏前后, HH和VV极化的散射能量对比会发生明显的反转现象, 并且多个极化组合参数在小麦倒伏前后特征变化显著, 因此这些极化特征可以用于倒伏现象的监测。

极化SAR特征的应用, 使得SAR信息在农业中的应用得到了进一步的深入, 已有这些研究结果均证明极化特征在农业应用中, 特别是在农作物识别、农作物长势参数反演及估产中的巨大潜力, 在未来可能成为精准农业实施重要手段之一。

3.3 SAR干涉特征

干涉技术最初发展的目的是利用简单的相位-高程关系($\varphi = k_z h$)获得对地形高程的测量。传统的干涉测量合成孔径雷达(Interferometric Synthetic Aperture Radar, InSAR)一般采用单波段、单极化方式进行,不考虑散射体的极化特征,用到的特征包括单极化的干涉相位和干涉幅度特征。极化干涉测量合成孔径雷达(Polarimetric Interferometric Synthetic Aperture Radar, PolInSAR)极化干涉特征在原有干涉幅度和相位特征的基础上又增加了极化特征,其利用全极化观测进行干涉处理,结合了干涉特征对空间分布敏感以及极化特征对散射体物理性质敏感的特性,可以同时把目标的精细结构特征与空间分布特征结合起来,提高干涉应用性能,并区分分辨单元内不同散射机制的垂直分布特征^[116]。

InSAR特征在植被中的应用主要基于干涉获得的相位特征中包含了“植被偏差”引起的相位特征。“植被偏差”引起的相位变化同时受到植被结构和SAR成像参数的影响,为了分析植被结构的影响,PolInSAR被用于“植被偏差”的监测。这些特征最早被用于森林高度的估测,根据可获取的特征、植被散射的特征发展了基于几何关系和基于物理模型的森林高度估测方法^[117]。InSAR和PolInSAR特征在农业中的应用目前主要集中在农作物高度的估测。重轨InSAR数据的时间失相干严重影响着其在植被覆盖区的应用:例如即使仅有24小时时间差的TanDEM数据也会受到时间失相干的影响,尽管如此,该数据的相干性与多种农作物的高度还是具有明显的相关性,在农作物高度估测中极具潜力^[118]。随着PolInSAR数据的丰富,一些研究者提出了适用于极化干涉SAR数据的植被散射模型,用于植被参数的反演。随机体地表散射模型(Random Vegetation over Ground, RVoG)和有向体地表散射模型(Orientation Vegetation over Ground, OVoG)为目前应用最广泛和最有代表性的两类植被散射模型。前者中的RV表示随机体,即电磁波在其中传播时衰减系数与极化状态无关,后者中的OV代表有向体,即电磁波在其中传播时衰减系数是极化的函数^[119,120]。RVoG和OVog模型经常被用于森林高度的反演,Lopez-Sanchez^[121]率先分析了这两类模型在农作物高度反演中的可行性和局限性,表明OVog模型更能描述农作物的散射特征,并且基于实验数据证实了其在玉米和水稻高度反演中的可行性。随后基于机载PolInSAR数据的农作物高度反演研究逐渐开展,基于RVoG模型的相位-幅度联合反演法被用于油菜、玉米、小

麦、大麦和甜菜的高度反演,研究结果表明该模型具有农作物类型依赖性,获得的油菜、玉米和甜菜的反演高度较好,标准差在0.20~0.31 m之间,而大麦和燕麦则较差,标准差在0.33~0.61 m之间。随着覆盖全球范围的无时间失相干的TerraSAR/TanDEM星载干涉、极化干涉SAR数据的丰富,基于该数据展开的农作物高度反演的研究近些年开始涌现。Erten等人^[122]和Rossi等人^[123]研究了覆盖水稻整个生长期的相位差变化,并用该信息分析了干涉相位和水稻冠层高度的关系,证实了HH和VV极化的选择会明显影响水稻高度估测结果;Lee等人^[124]基于TerraSAR/TanDEM干涉SAR数据,提出了水稻生长区地相位的估计方法,采用RVoG模型和对照表法反演了研究区水稻的高度,反演结果的RMSE为0.10 m;国贤玉等人^[125]采用双极化TerraSAR/TanDEM干涉SAR数据发展了RVoG模型,并用于水稻高度的反演,研究表明当水稻株高高于0.4 m时,可以取得较好的估测结果,反演值与真值的 R^2 为0.86,均方根误差为6.79 cm。

已有针对不同农作物高度反演的结果充分表明了干涉、极化干涉特征在农作物垂直结构变化相关监测中的潜力。然而由于农作物覆盖区体散射受时间失相干影响严重,使得重轨干涉影像噪声较大,影响反演结果,因此其广泛应用受到了较大的限制。随着无时间失相干数据的出现,使得采用干涉、极化干涉SAR特征进行农作物垂直结构监测成为可能,目前尽管已经展开了一些研究,但是干涉特征在农业应用中的潜力还有待进一步挖掘。

3.4 SAR层析特征

层析SAR技术(SAR Tomography, TomoSAR)的提出是为了实现地物垂直方向上的观测,目前SAR应用中,主要有两种层析技术:一种是多基线SAR层析技术,即在垂直于视线方向上增加多幅干涉天线来对观测场景实现重复观测,相当于在垂直于视线方向上合成一个较大的孔径来获得高度维的特征,通常通过谱分析方法来获得场景沿垂直方向的散射值^[126-128];一种是利用不同极化状态下的干涉相干系数反演植被垂直结构分布的极化相干层析技术,即利用不同极化的干涉相干变化来重建观测场景后向散射随高度变化的方程,然后利用观测的相干数据获得植被高度和地形相位,将获得的植被高度和地形相位特征带入以傅里叶-勒让德级数展开的垂直结构方程,求解各系数获得场景沿垂直方向的散射值^[126,128,129]。多基线SAR层析技术的成像算法包括三大类:非参数谱估计方法、参数谱估计方法、稀疏谱估计方法。稀疏谱估计方法可以有效

的解决SAR层析成像中由于基线非均匀分布采用插值计算方法中计算量大、耗时费力的弊端,提高了层析SAR数据处理的效率,近年来基于此发展了大量相关的成像算法^[130,131]。已有研究发现:单基线极化相干层析技术仅能提高混合表面/体散射的体散射层深度和地表相位特征,无法真正得到目标的垂直向结构信息。双基线比单基线的分辨率高,但当基线数量超过3时,该方法的稳定性下降;此外该方法需要输入先验知识,如地相位和植被高度,这些信息通过PolInSAR技术获得,因此一方面存在对植被高度的低估,另一方面很大程度上依赖PolInSAR技术的发展^[129,131]。

SAR层析技术的应用目前仍然处在应用研究的初期,其在农业中的应用也刚刚展开。SAR层析技术目前被广泛用于森林生物量的反演^[131],但是由于农作物生长变化的快速性及其复杂环境场景的影响,目前的研究多集中在农作物高度参数反演、各个频段农作物整个生长期垂直方向的后向散射变化、农作物覆盖区的地表、体散射的区分中^[3,132-139]。初期研究者们采用室内和室外地基雷达实验数据对X-, C-和L-波段小麦、玉米的三维散射剖面进行了研究,探索了其受到极化方式、入射角和频率的影响^[133-135]。随着机载TomoSAR数据的出现, Pichierrri等人^[139]采用机载TomoSAR数据研究了层析特征在农田场景的应用可行性。他们以OVoG模型为基础,采用双基线极化相干层析的方法分析了X-, C-和L-波段在小麦、燕麦、玉米和油菜高度反演中的可行性。研究结果指出了基线长度、频率对不同农作物高度反演的影响:基线较小时,极化干涉相干性与农作物高度的敏感性降低;L-波段用于油菜、玉米高度反演时,均方根误差约为10%,而X-波段用于大麦和小麦等谷物的高度反演时,均方根误差低于24%。Joerg等人^[132]采用Capon非参数谱滤波方法获得了玉米、大麦和小麦在X-, C-和L-波段不同生长期的垂直方向后向散射剖面图。从获取的垂直剖面图中可以看出,玉米覆盖区具有明显的二次散射机制;小麦冠层具有明显的表面散射机制,并且田垄散射的影响明显;大麦的HH散射特征几乎不可见。基于这些农作物覆盖区的散射剖面,这些研究者们进一步分析了采用其进行体散射和地表散射机制分离的可行性及有效的方法。由于农作物在整个生长周期中变化的快速性,时间序列TomoSAR数据的获取对其在农业中的深入应用也有着显著的影响,这些研究同时也说明了时间失相干对极化干涉相干层析特征在农作物监测中的影响^[132,140]。

SAR层析特征在提高农作物分类精度、农作物

高度和生物量反演精度中具有重要的潜在应用价值。然而目前该特征在农业中的应用还较少,反演的方法、应用的农作物对象等还存在较多的探索空间,随着多基站SAR观测技术的实现,新体制SAR卫星计划的实施,层析SAR特征在农业中的应用需要未来进一步深入研究。

4 总结与展望

4.1 总结

目前雷达技术在农业中的多个方面均展开了应用研究,也取得了丰硕的研究成果。然而,在农业应用中,不同的利益相关组织或个人关注和需求的农情信息不同,对雷达技术在农业各领域中的应用的需求也不尽相同。尽管目前在各个领域都有一些研究结论,但是针对具体的需求和深入的应用都需要进一步的探索 and 开发。例如在农作物识别和分类方面,尽管也出现了全球尺度的分类产品,但是这些产品偏重于用地表覆盖类型的划分,而精细的农作物类型的划分则存在不少问题;此外农作物识别和分类的研究成果多集中在成片的同质性区域,对于斑块破碎、种植类型复杂的区域,则很难达到需求的精度。以精准农业为例,在具体的需求中更需要了解在农业中这些田地是如何使用的,在整个农作物生长过程中田间操作是如何实施的。农业灾害类型较多,多种灾害对农作物产量影响严重,特别是洪涝灾害监测是雷达监测的优势,然而目前相关的研究也开展较少。粮食产量的预估是目前各国政府和相关利益人或组织均关注的问题,目前基于雷达技术的估产研究较少,方法多集中在利用后向散射系数与农作物产量做简单的经验统计,尽管可以得到粗略的产量结果,但是估计结果的质量如何,相关的研究则展开较少,已有的研究也多集中在农田同质性较强的国家和地区。尽管目前也采用同化的方法展开了部分估产的研究,但是目前还集中在理论的研究,并且其在大区域、异质性强的地区的研究也相对较少。

雷达技术的发展过程本质上也是对微波电磁波资源不断发掘和利用的过程。通过对各类雷达特征在农业中应用可知:雷达各类特征在农业中的应用差异较大,目前应用最广泛的特征是后向散射特征和极化特征,而SAR影像中的干涉、极化干涉和层析特征在农业应用中的相关研究则刚刚展开。后向散射系数应用较多的领域是农作物长势参数和土壤水分的反演。在长势参数反演中多基于经验和半经验模型,研究对象主要为水稻,而不同的农作物、相同农作物在不同生长期的散射机制变化明显,直

接影响后向散射特征,这使得这些经验和半经验模型的广泛应用受到极大的限制;另外目前的半经验模型和机理模型多为非相干散射模型,无法利用SAR数据的相位特征。土壤水分反演的模型多基于特定的土壤观测数据建立,在大面积的土壤水分反演时不确定性较大,另外对相位特征也没有有效的利用。极化特征应用较成熟的领域是农作物识别、分类和农作物长势参数反演。目前基于极化特征的农作物分类局限在同质性区域,散射机制较简单的几类农作物的分类中,对于一些散射机制复杂的作物,其极化散射机理仍然不明确,其相应的分类方法也还在研究中。在采用极化分解参数进行的农作物长势参数反演中,由于多数分解方法假设农作物冠层由匀质散射体构成,这样构建的模型无法描述农作物冠层复杂的散射情况,从而使得反演结果不确定性增大、适用性降低。此外,长势参数反演和农作物估产的研究中,目前对于农作物生长的水文、气象、环境等影响因子考虑较少,无法全面揭示农作物生长及产量形成的机制。

4.2 展望

雷达遥感的独特优势使得其在农业遥感监测中可以发挥重要的作用,经过几十年的发展,雷达在农业中的应用由初期的地面观测,逐步发展到机载和星载观测。传感器从最初的散射计发展到现在的多频、多极化、多角度、多时相等多维SAR观测。目前雷达遥感在农作物识别和分类、农田参数反演、农作物长势参数反演、农作物物候期划分等方面均取得了诸多的进展,但在农作物灾害监测和农作物估产中的研究则还处在实验阶段,并且目前在农业领域应用相关的技术和方法多数仍处在研究阶段,在实际应用中还未进行大范围推广和实施。造成该现状的原因一方面是由于发展的方法、模型等还具有一定的局限性,需要进一步改进和发展;另一方面是由于目前支撑农业实时监测的SAR数据资源还相对匮乏,像极化干涉SAR数据、层析SAR数据等目前多依赖国外的机载和部分星载实验数据,使得深入分析和研究稳健的算法和模型受到限制。在灾害监测中,由于对多种灾害的微波散射机制还未完全明确,因此目前应用的还较少;而作物的准确估产又依赖于作物生长状态,而作物生长状态信息与SAR信息融合的研究还处于研究的初级阶段。在目前农业应用中,被动微波遥感数据由于获取方便、时间分辨率较高且数据处理简单,可以成为雷达遥感在农业中应用的有效补充。尽管如此,雷达技术在农业中的应用已经展现出极大的优势和潜力,正成为推动精准农业、智慧农业有效实施、

高效快速发展的有力手段。随着SAR数据类型、成像模式丰富,基于多频、多极化、多角度、多时相等多维SAR观测将成为可能,未来农业领域的应用不仅要细化各维度SAR特征在农业各领域的方法和模型,还要结合农业行业各相关利益人的需求,从而推动雷达技术在农业领域的深入、有效利用。

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Review of Application of Radar Remote Sensing in Agriculture

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Abstract: With its all-weather data acquisition capability, allowing it to more deeply penetrate into vegetation than optical sensors can, as well as its sensitivity to the shape, structure, and dielectric constant of vegetation scatterers, active radar remote sensing technology has great potential in agriculture monitoring. In this paper, we introduce radar application in crop identification, cropland soil moisture inversion, crop growth parameter inversion, crop phenology retrieval, agricultural disaster monitoring, and crop yield estimation. An overview of several specific reviews focusing on the aforementioned fields is given. Then, we discuss the results and conclusions on the basis of information extracted from radar scatterometers and synthetic aperture radar. Finally, we summarize the problems and reasons for radar application in agriculture, and present the future trend of radar application in agriculture.

Key words: Radar remote sensing; Agriculture; Backscattering characterization; Polarimetric characterization; Interferometric characterization; Tomography characterization

CLC index: TN957.52

Document code: A

Article number: 2095-283X(2020)03-0444-18

DOI: 10.12000/JR20051

Reference format: ZHANG Wangfei, CHEN Erxue, LI Zengyuan, *et al.* Review of applications of radar remote sensing in agriculture[J]. *Journal of Radars*, 2020, 9(3): 444–461. DOI: 10.12000/JR20051.

1 Introduction

1.1 Research background

Radar is one of the main sensors in microwave remote sensing application. Microwave remote sensing technology has three main advantages: (1) Microwaves can penetrate clouds and even rain; (2) they can penetrate vegetation more deeply than light waves can; and (3) the information obtained by microwaves, which is different from that acquired by optical remote sensing sensors, can reflect the geometric and dielectric properties of objects^[1]. Radar has great potential in agricultural monitoring because of its all-weather and all-day monitoring ability; its sensit-

ivity to the vegetation shape, structure, and dielectric constant; and its ability to penetrate vegetation.

Currently, the applications of radar remote sensing in agriculture mainly include crop classification and identification, farmland parameters (water content and surface roughness) inversion, crop growth parameters (biomass, Leaf Area Index (LAI), and height) inversion, phenological stage retrieval, crop disaster monitoring, and crop yield estimation.

Crop classification and identification are the initial key applications in agricultural situation monitoring using remote sensing technology. Accurate crop type identification is the basis of accurate crop planting area estimation, structure, and spatial distribution extraction. It can also provide key input parameters for crop yield estimation models^[2]. Different crops have different canopy structures, geometric features, and dielectric constants; therefore, they have different scattering characteristics in Synthetic Aperture Radar (SAR) images, especially in the images acquired

Manuscript received April 30, 2020; Revised June 15, 2020; Published online June 28, 2020.

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Foundation Items: The National Natural Science Foundation of China (31860240), The National Key R & D Program of China (2017YFB0502700)

Corresponding Editor: LIAO Mingsheng

with different frequencies or polarizations. However, the phenomenon is also the theoretical basis for crop classification and recognition with radar remote sensing.

Soil moisture content inversion is one of the most conventional applications of radar remote sensing applied in farmland parameter inversion. Surface roughness has a great influence on the inversion of farmland soil water content, especially in bare soil water content inversion, and it is an important parameter in agronomy, agrology, geology, and climatology. Therefore, surface roughness inversion has developed into an independent branch of study^[3]. The crop vegetation effect should also be considered in the inversion of farmland soil moisture content in areas covered by crops. The soil water content in farmland is usually estimated by establishing the relationship model between radar backscattering coefficient and soil volume water content. The radar backscattering coefficient and soil moisture content have a good correlation after the effect of vegetation canopy and soil roughness is separated from the radar signal^[2-4].

Crop growth status and trend directly affect crop yield and quality^[5]. Crop growth parameters mainly include biomass, LAI, height, and density. Growth parameters are usually effective indicators of crop growth status. Therefore, crop growth monitoring is typically achieved by growth parameter inversion. The backscattering information, polarization characteristics, and interference characteristic information of radar are often used in crop biomass, LAI, and height inversion.

Crop phenological information is one of the important characteristics of agricultural ecosystem and is an important basis for agricultural production, field management, planning and decision-making. The division of crop phenology mainly refers to the identification of the period that corresponds to significant changes that occurred according to crop morphology during the crop growth period from emergence to harvest^[6-8]. Polarimetric information is sensitive to crop structure and morphological changes. Therefore, polarimetric SAR data have been widely used to

identify crop phenology in recent years.

Many kinds of crop disasters exist, including flood, drought, diseases, insect pests, and lodging. At present, the application of radar remote sensing in crop disasters has not been fully explored, and most existing research focuses on lodging monitoring, especially for crops that have an obvious vertical structure, which mainly takes advantage of the sensitivity of polarization characteristics to the changed crop structure during lodging^[9].

The ultimate goal of agricultural remote sensing monitoring is to estimate crop yield accurately and in a timely manner. Crop yield can be estimated by using a crop growth model and remote sensing. The former can simulate the growth of crops at a single point level by mathematical modeling and could achieve the single-point yield estimation of crops with high precision; the latter can obtain the comprehensive characteristics of crops at a regional level. The advantages of the two methods are complementary, and integrating and applying them in crop yield estimation can improve the accuracy and mechanization of yield estimation^[9]. Several current applications of radar remote sensing in crop yield estimation are the assimilation of remote sensing data and crop growth model to estimate crop yield, but this field has not been fully explored yet^[3].

1.2 Overview of existing research

With the development of radar remote sensing technology and its application in agriculture, many researchers have reviewed related research on the application of radar remote sensing technology in different fields of agriculture. Wang Di *et al.*^[2] reviewed the SAR technology application progress in crop classification and recognition, and they concluded that SAR features that are currently used for crop identification and classification include single-band, single polarization, multipolarization, and multiband features; and the classification methods include algorithms based on the pixel statistical characteristic polarization decomposition analysis and the theory of crop scattering mechanisms. They also pointed out that the current accuracy of recognition and classification is still low, with the recognition accuracy be-

ing less than 85%, which may have resulted from the lack of research on the mechanism-related classification algorithms. Shi Jiancheng *et al.*^[4] summarized the radar data sources used in soil moisture inversion, the limitations of each data source, current algorithms, and deficiencies. Liu Jian *et al.*^[10] summarized the influence of roughness and covered vegetation on soil water inversion and corresponding solutions. They pointed out that the accuracy and universality of existing inversion methods need to be further improved, and the fusion of SAR data from different observation modes (multiband, multipolarization, and multiangle) is an effective direction in future inversion tasks. Liu *et al.*^[3], McNairn *et al.*^[11] summarized the potential of crop growth monitoring using SAR technology. They stated that current crop growth parameters used for crop growth potential monitoring include biomass, LAI, and height, and the used SAR features include backscattering, polarization, and interference characteristics. Li Pingxiang *et al.*^[9] briefly reviewed crop phenological period monitoring based on SAR technology and found that the main methods currently include two categories: methods according to classification and ones based on temporal dynamic tracking. They also concluded that the application of SAR technology in agricultural disaster monitoring currently focuses on crop lodging. Huang Jianxi *et al.*^[12,13] reviewed the application of remote sensing and crop growth model data assimilation in crop yield estimation, and observed the potential of assimilating SAR remote sensing data and crop growth model in crop yield estimation. However, the method has rarely been explored, and it may be one of the main development directions for crop yield estimation in the future.

The advantages and disadvantages of the application of radar remote sensing in agriculture had been explained from many aspects, and they have positive significance to promote the application of radar remote sensing technology in agriculture. However, with the development of SAR technology and the promotion of application requirements, SAR data acquisition methods developed from single frequency, single polarization,

and single angle to multifrequency, multipolarization, multiangle, and multi-time equal comprehensive acquisition methods. With the changes in the SAR observation mode, the scattering mechanism of crops and its characterization in SAR images become more complex. The changes in SAR observation modes affect not only the cognition and understanding of crops by using SAR technology but also the applicability of traditional estimation methods in agricultural applications under the joint observation dimension. To meet the requirements of multidimensional SAR observation technology, the extraction methods of SAR parameters and their responses to the relevant parameters systematically need to be organized^[14]. Primary studies mainly used radar scatterometer for agricultural-related research, and SAR is the sensor that has been used most recently. Previous reviews mainly focused on SAR application. The initial research based on radar scatterometer is the experimental basis for the subsequent application of SAR technology, and their verifications of the research results on microwave remote sensing theory provide theoretical guarantee for further development of SAR technology. Therefore, a comprehensive review and summary of the scatterometer-related research results are necessary. Some of the existing review literature was published earlier, and the latest research results have not been added, especially the literature on the application of interference, polarized interference SAR technology, and tomographic SAR technology in agriculture. In accordance with the above summary, in this paper, we first summarize the current situation of radar scatterometers in agricultural application. Then, we review the application status of various SAR techniques in various agriculture fields on the basis of different SAR observation techniques to determine the advantages and disadvantages of SAR technology in the whole agricultural system comprehensively. Finally, we propose possible directions and ideas for further SAR application in the agriculture in the future.

2 Application of Radar Scatterometers in Agriculture

Research on the application of radar scattero-

meters in agriculture mainly focuses on the inversion of soil moisture in farmland. The initial research explored its application in vegetation canopy structure, crop mapping, crop growth monitoring, crop identification, and classification. However, such research is fewer in number than that on soil moisture. In the following sections, we summarize the application of scatterometers in agriculture according to the remote sensing platform, such as ground-based, airborne, and spaceborne scatterometers.

2.1 Ground-based radar scatterometer

Radar scatterometers measure the scattering cross section of targets. The information can be used to understand the interaction mechanism between microwaves and the natural target. Scatterometers transmit a series of pulses and measure their echo, and then quantify the returned echo characteristics to obtain the scattering cross section measurement results of the target. The platform of scatterometers includes satellite borne, airborne, and ground. The ground platform is carried mainly on a high tower or a truck; scatterometers placed on such a platform are also referred to as ground-based scatterometers. The scattering cross section of the target measured by scatterometers is affected not only by the characteristics of the target itself but also by the frequency, incidence angle, and polarization mode of the scatterometers^[15].

Tab. 1 summarizes the research conducted by using ground-based radar scatterometers and their related conclusions. Research on soil moisture inversion based on ground-based scatterometers began in the late 1960s and early 1970s. Previous studies provided theoretical and experimental support for the optimal parameter setting of space-borne scatterometers and space-borne SAR, which were applied in related research. A research group from the University of Kansas used Microwave Active and Passive Spectrometer (MAPS) or Microwave Active Spectrometer (MAS) to study the reflection of backscattering coefficient on soil moisture change. The frequency of the MAPS and MAS in these tests ranges from 1 to 18 GHz, and the incidence angle

ranges from 0° to 80°. The following results were obtained: the inversion of soil moisture by backscattering coefficient was affected by frequency, polarization, incidence angle, soil roughness, and covered vegetation; the influence of soil roughness could be eliminated or reduced by selecting appropriate frequency and incidence angle; and scatterometers with low frequency and small incidence angle were more suitable for soil moisture inversion. The polarization characteristics were also sensitive to the change in crop structure. Different crop types were distinguished more easily with the combination of polarization, high frequency, and large incidence angle^[16-23]. Radar Observation of Vegetation (ROVE) was performed in the Netherlands to study the response of X-band polarimetric backscattering to crop parameters under different incidence angles. The results showed that when the crop coverage rate reaches a certain degree, the backscattering coefficient will be saturated; multifrequency observation could improve the estimation accuracy of crop growth parameters, and it also confirmed that a large incidence angle was more suitable for vegetation monitoring^[24-27]. On the basis of Ka-, Ku-, X-, C-, and L-band ground-based scatterometer data, Japanese scholars Inoue *et al.*^[28] pointed out that C-band was suitable for LAI inversion, while L-band was suitable for biomass estimation. According to the research of the Canadian Remote Sensing Center, HV polarization performed well in crop type identification and crop stubble identification. They also pointed out that backscattering had an obvious response to the dynamic change of daily water content in farmland area, but their correlation was affected by frequency and crop growth stage^[29-33]. Chinese researchers had mainly explored the backscattering changes of soil moisture at different polarizations and incidence angles at the X- and C-bands. Their findings showed that ridge orientation significantly influenced the backscattering of co-polarization mode; in soil water content inversion, the influence of roughness could be eliminated by selecting data with a specific incidence angle^[34-37]. A similar conclusion was obtained by other experiments^[38-42].

Tab. 1 Summary of studies using ground-based radar scatterometers

Research team	Description of scatterometer parameters		Type (object)	Conclusion	Reference
	Parameter	Description			
MAPS	Dual polarization (HH+VV); the incidence angle varies from 0° to 70°; the frequency ranges from 4 to 8 GHz	Soil moisture	The sensitivity of backscatter to soil moisture: HH > VV; the sensitivity of backscatter to soil water is significantly affected by the soil surface roughness, which can be characterized by the change in frequency and incidence angle. Therefore, soil moisture inversion is obviously affected by frequency and incidence angle. When the frequency ranges from 4 to 8 GHz, the sensitivity of backscatter to soil water is significantly affected by the frequency and incidence angle. For instance, when the incidence angle varies between 5° and 15°, the backscattering of HH polarization is hardly affected by the vegetation and only reflects the change of soil moisture.	[16–18]	
	Full polarization (HH+VV+HV+VH); the incidence angle varies from 0° to 80°; the frequency is between 4 and 8 GHz	Classification and mapping of crops (crops include corn, sorghum, soybean and alfalfa)	The polarization characteristics were sensitive to the change in crop structure; the ridge direction of farmland has an obvious influence on the polarization scattering characteristics, which is dependent on the type of crops; the sensitivity of the changes to crop structure: VV > HH; the changes in crop density and incidence angle affect the backscattering intensity of microwave at different frequencies; the combination of large incidence angle (30° to 65°) and high-frequency band would be the most effective way to distinguish different crop types.	[18]	
Ulaby Team, University of Kansas	Bipolarization (HH+VV); the incidence angle varies from 7° to 15°; the frequency is between 2 and 8 GHz	Soil moisture in bare soil-covered area	Soil roughness affects the inversion of soil moisture in bare soil coverage area; the influence of soil roughness can be reduced by optimizing the system parameters of scatterometers. The recommended combination is a frequency of 4 GHz, an incidence angle that varies from 7° to 15°, and a polarization mode of HH or VV. This parameter is also applicable to soil moisture retrieval in vegetation coverage areas with frequencies ranging from 4 to 8 GHz. The highest correlation between backscatter and soil moisture is obtained at a frequency of 4.7 GHz and an incidence angle of 10°.	[18,20]	
MAS	Tri-polarization (HH+VV+HV); the incidence angle varies from 0° to 80°; the frequency is between 2 and 8 GHz	Soil moisture, surface roughness, and soil structure	For the soil moisture in the bare soil-covered area, the conclusion was similar to Ref. [20], and the surface roughness effects are the lowest when the frequency is 5 GHz and the incidence angle ranges from 7° to 17°. The best soil moisture inversion with crop coverage was obtained at a frequency of 4.25 GHz, incidence angle of 10°, and polarization of HH, with $r = 0.92$; The estimation capability of soil moisture based on backscattering coefficient depends on the proportion of soil moisture to the field water contents. When the proportion is less than 50%, the estimation is not good, and when the proportion is between 50%–100%, the estimation performance is better.	[21–23]	
	Bipolarization (HH+VV); the incidence angle varies from 0° to 70°; the frequency is between 8 and 18 GHz	Soil moisture and crop identification (corn, sorghum, soybean and alfalfa)	In addition to the similar conclusion with Ref. [18], the best crop identification can be obtained by using the multifrequency data of VV; the influence of soil moisture on crop identification can be minimized when the incidence angle is between 30° and 65°, and better soil moisture inversion results can be obtained with the data combination of low frequency and small incidence angle.	[19]	

续表 1

Research team	Description of scatterometer parameters		Type (object)	Conclusion	Reference
	Parameter	Description			
ROVE, the Netherlands	FM/CW	X-(10GHz);Q-band (35 GHz); the incidence angle varies from 15° to 80°; polarization: VV, HH, VH, HV	Crop observation; Soil moisture	The backscattering coefficient of crops is obviously affected by polarization mode and observation angle. The influence of imaging geometry depends on crop types. For example, the influence of incidence angle on sugar beet is not obvious, but the impact on potato reached -5 dB. In addition, when the coverage rate of crop canopy reached 80%, the variation of backscattering coefficient was saturated. X-band can be used for agriculture crop classification and identification. Multifrequency data joint observation can improve the accuracy of crop canopy biomass, canopy water content, coverage, and crop height estimation. Increasing the observation incidence angle can improve the estimation accuracy of canopy water content.	[24-28]
CCRS,Canada	FM/CW	L-/C-/Ku (1.5/5.2/12.8 GHz); full polarization; incidence angle: 0°-85°	Crop identification and classification; soil moisture, crop canopy moisture, crop residue	Through the analysis of variance coefficient, we can obtain the best crop recognition with Ku-band, HV polarization, incidence angle range of 30°-60°, and crop growth during 29-30 weeks. A high correlation exists between backscatter and daily canopy water content when the crops grow in the rapid growth stage. The correlation between backscatter and daily soil moisture change is high when the crops wither. HV is sensitive to crop residual change and is not affected by observation direction or ridge direction.	[29-33]
	Ground based microwave scatterometer (FM/CW)	C-; HH and VV	Soil moisture Soil roughness	The ridge direction enhances the backscattering coefficient with the polarization channel parallel to it, and the measured roughness by SAR is different from that obtained by optical data.	[34,35]
China	Microwave scatterometer (FM/CW)	X-(9.375 GHz), Incidence angle: 0°-48°; step interval: 6°; full polarization	Soil moisture	X-band with HH polarization has the highest sensitivity to bare soil water content at an incidence angle of 6°. X-band is worse than C-band for vegetation coverage soil moisture retrieval. When the water content is constant, the backscattering coefficient decreases with the increase in the incidence angle, and the change rate decreases with the increase in roughness. With the increase in frequency, the incidence angle independent of roughness increases. For example, when the frequency is 1.1 GHz, the incidence angle is 7° and 10° at 7.5 GHz.	[34,36,37]
	ComRAD	Bipolarization, 1.4 GHz radiometer; full polarization (1.25 GHz)	Vegetation Water Content (VWC)	L-band and HV showed the best performance in VWC retrieval when HH, VV, MPDI, and RVI are used to retrieve VWC.	[38-40]
Others	UF-LARS	L-(1.25 GHz), full polarization; incidence angle: 40°	Soil moisture, Crop growth	The accuracy of soil moisture retrieval can be improved by decreasing the sampling time interval, and VV polarization backscattering is more sensitive to the vertical structure of crops. The linear relationship inversion results are uncertain in the inversion of soil moisture where the scattering mechanism is dominated by vegetation scattering, while the surface is smooth and the soil is dry.	[41-42]

2.2 Airborne and space-borne radar Scatterometer

Although ground scatterometers are easy to operate and are low cost, the observation results are greatly affected by geometric relations and the limited observation range, which is due to the low

observation platform. An airborne platform with a larger observation range can expand the observation range and improve the observation efficiency. The airborne platform is mainly used as a compensation to the ground platform, and it

provides theoretical and experimental support for the parameter setting of the onboard space-borne radar sensor. In the ROVE project, the data of airborne radar with side view are included. Kurl *et al.*^[42] used the data to study the variation of X-band backscattering coefficient during the whole crop growth period, and they found that the dynamic range is from 3 dB to 15 dB. Many research results were obtained based on 1–18 GHz DUTSCAT in Europe and the ERASME airborne scatterometer at C-/X-band^[43,44]. Bouman *et al.*^[45] and Ferrazzoli *et al.*^[46] confirmed the results of Ref. [27] by using the multifrequency data of DUTSCAT and pointed out that X-band and Ku-band were suitable for crop classification, while L-band was more suitable for soil moisture inversion. Benallegue *et al.*^[47] analyzed the feasibility of soil moisture inversion by using multifrequency and multiangle data of ERASME and obtained a similar conclusion as Refs. [16–23].

According to the ground-based and airborne experimental results, the main working bands of the space-borne scatterometers are C-(5.3 GHz) and Ku-(13.5 GHz) band. C-band space-borne scatterometers with a longer wavelength are less affected by cloud and rain, while Ku-band with a high frequency is more sensitive to changes in target characteristics. Tab. 2 lists the main information of the main space-borne scatterometers to date^[48–51]. Space-borne scatterometer data were mainly used in soil moisture inversion and crop parameter inversion in agriculture. WoodHouse *et al.*^[52,53] used ERS-1 AMI scatterometer data to retrieve vegetation coverage, soil moisture under vegetation cover, and seasonal variation of vegeta-

tion. The soil moisture retrieval results were affected by vegetation coverage and had regional dependence; the observation results of vegetation seasonal change were affected by air and surface temperature, according to Frison *et al.*^[54]. Frolking *et al.*^[55] used QuickSCAT SeaWinds to monitor the phenological periods of multivegetation at 27 sites in the United States. The results were compared with MODIS LAI data; the results were basically consistent, but the phenological periods monitored by backscatter characteristics were always earlier than those estimated by MODIS LAI data. The results acquired by Lu *et al.*^[56] using the same data at 22 sites in China were consistent with the results in the United States. Wen *et al.*^[57] used ERS-1 AMI data to retrieve soil moisture in Tibet. The correlation between scatterometer estimation results and 0–4 cm surface soil moisture from a ground survey reached 0.78. On the basis of the data of a space-borne scatterometer, several scholars completed global soil moisture mapping^[58,59], and some scholars pointed out that global soil moisture mapping should consider the influence of the dynamic changes of surface vegetation^[60]. To provide an analysis method for NASA SMAP data, Kim *et al.*^[61,62] used Monte Carlo simulation to study the forward scattering model. They studied the models that were suitable for 16 vegetation and bare soil surfaces, and then the models were used to simulate soil dielectric constant, roughness, vegetation water content, and other parameters. On the basis of these data, Naemi *et al.*^[63] and Wagner *et al.*^[64] optimized the inversion algorithms and models.

Tab. 2 Major space-borne radar scatterometers and their basic information

Satellite	Sensor	Band	Incidence angle	Polarization	Service time	Nation
Seasat	SASS	Ku	25°–55°	HH, VV	1978.6–1978.10	US
ERS-1	AMI	C	18°–59°	VV	1991.6–2000.3	ESA
ERS-2	AMI	C	18°–59°	VV	1995.4–	ESA
ADEOS-1	NSCAT	Ku	18°–63°	HH, VV	1996.8–1997.6	US
QuickSCAT	SeaWinds	Ku	46°, 54°	HH, VV	1999.7–	US
ADEOS-2	NSCAT	Ku	46°, 54°	HH, VV	2002.12–2003.8	US
SZ-4	CN/SCAT	Ku	37°	HH, VV	2002.12–	China
MetOp-1	ASCAT	C	25°–65°	VV	2006.10–	ESA
OceanSat-1	OSCAT-1	Ku	50°, 57°	HH, VV	2009–	India
HY-2A	HY-2A	Ku		HH, VV	2010.8–	China
OceanSat-2	OSCAT-2	Ku	50°, 57°	HH, VV	2016–	India
	SMAP	L-			2015.1–2015.7	US

Early research based on ground-based and airborne scatterometer data described the feasibility of using backscatter characteristics for soil moisture inversion and crop classification. The application of space-borne scatterometers further optimized the early inversion method and promoted the application of space-borne scatterometers in soil moisture and vegetation parameter inversion. With the development of imaging radar, SAR technology in particular has been widely used in various fields of agriculture. However, scatterometer observation still plays an important supplementary role in SAR application in agriculture because of its flexibility, low cost, and rapid-repeat observation ability.

3 SAR Application in Agriculture

Compared with scatterometers, SAR can provide not only backscattering characterization but also image features and other observations. In recent years, SAR has been widely used in agricultural monitoring. On the basis of the data that SAR technology can provide, features applied in agriculture can be divided into four aspects: backscattering, polarimetric, interferometric, and tomography features. Tomography feature is a further development of interferometric or polarimetric interferometric feature in vertical space.

3.1 Backscattering characterization of SAR

Only single frequency and single polarimetric images can be obtained from the early SAR data (from the end of the 1980s to 2002); the only feature that can be extracted is backscattering. Most of the applications of SAR backscatter feature in agriculture were based on the further verification and deepening of backscattering information of scatterometers applied in agriculture. Therefore, most of the initial research verified the research results on the basis of scatterometer data, and the methods were mostly based on that developed from scatterometer research^[65–70]. The unique scattering mechanism of rice underlying surface (water surface) makes rice distinct from other crops. Therefore, most initial research on crop recognition based on backscattering coefficient used rice as the research object. The classification accuracy of using these features for rice recognition can

reach 80%, 91%, and 98%^[65]. However, most of the study areas in the above-mentioned research were homogeneous, and the accuracy of classification and recognition was significantly reduced in areas with fragmented plots and complex planting structure^[65,66]. In the inversion of soil moisture and crop growth parameters, the models between backscatter and inversion parameters were established. These models included the empirical, semi-empirical, and mechanism models. The empirical model is usually established by experimental observation data, thereby making it sensitive to the conditions obtained from experimental data, such as meteorological conditions, imaging geometry, crop conditions, crop types, phenological characteristics, and soil moisture. These sensitive features cause the uncertainty of inversion results and reduce the applicability of the model. Given these limitations of the empirical model, some researchers began to develop the semi-empirical model and the mechanism model. The Integrated Equation Model (IEM), the Advanced Integral Equation Model (AIEM), and the improved models based on these two models were widely used in the inversion of bare soil moisture on the basis of backscattering. The commonly used algorithms include change detection method, regression analysis method, and model-based artificial neural network method^[67]. Water Cloud Model (WCM) is a representative semi-empirical model for vegetation parameter retrieval^[68]. The mechanism model is MICHigan MICrowave Canopy Scattering (MIMICS). These two models are used to reduce the impact of vegetation on soil moisture retrieval in vegetation coverage areas. The accuracy of these two models in the retrieval of growth parameters was enhanced by many scholars by introducing more features^[70–75]. Ref. [3] summarized the detailed application status of these two models in agriculture. At present, the backscattering coefficient is the most commonly used feature in crop yield estimation using radar data. Two kinds of methods are used for crop yield estimation: the use of backscattering coefficient to estimate crop yield directly and the estimation of crop yield by assimilating the estima-

tion results of growth parameters based on backscatter with a crop growth model. The direct use of backscattering coefficient for yield estimation is usually performed to establish the relationship model between backscattering coefficient and yield, and then to retrieve the yield, which belongs to the empirical model. Although it can obtain better estimation accuracy in a specific area, it is affected by the defects of the empirical estimation model, so it is difficult to use widely^[76,77]. Research on the assimilation of SAR remote sensing information and crop growth model began only in recent years. At present, the information used for assimilation mainly includes biomass and LAI retrieved from SAR backscattering characterization^[78,79].

3.2 Polarimetric characterization of SAR

Full polarimetric SAR data began to be collected in the early 1990s. The data of scattering amplitude and phase characteristics of HH, HV, VH, and VV polarization were recorded. Polarimetric feature extraction methods usually include polarimetric synthesis and polarimetric decomposition. The backscattering of any polarization mode can be calculated by using polarimetric synthesis technology, thus improving the detection of ground objects. Polarimetric decomposition technology can refine the characterization of ground objects and enhance the detection ability of ground objects. Polarimetric features are sensitive to the physiological characteristics of crops and the scattering direction and shape of crops. Thus, they have great potential in various agricultural research fields and are also the most widely used and deeply studied in agricultural applications. [Tab. 3](#) lists the current applications of polarimetric characterization in the main agricultural fields.

[Tab. 3](#) shows that polarimetric characterization had been applied in agriculture research. Crop recognition and classification was the earliest application of polarimetric features in agriculture. In early research, crop classification accuracy was improved by adding different polarization backscattering characterizations. The crop classification accuracy effectively improved with

the addition of polarimetric features, improving by 37% in some regions^[91,92]. With a variety of proposed polarimetric decomposition methods, various studies showed that the introduction of different polarimetric decomposition parameters can effectively improve the classification accuracy, which varied from 70% to 96%. Some studies classified crops such as corn, soybean, wheat, and rice, and others included crops and forests, bare soil, and buildings^[93-95]. Ref. [\[65\]](#) summarized the classification methods using these features in detail. In farmland soil moisture inversion, polarimetric characterization can effectively reduce the uncertainty of inversion based on backscattering characterization only^[96,97].

Many scholars proposed several inversion algorithms by using multipolarimetric data to improve the inversion accuracy of soil moisture^[98-100]. After polarimetric characterization was added, the Root Mean Square Error (RMSE) of soil water content inversion decreased by around 4%^[98]. The sensitivity of polarimetric characterization to soil roughness was first confirmed by the response of polarimetric synthesis parameters. The parameters related to circular polarization were the most sensitive to soil roughness^[101]. Subsequently, the polarimetric decomposition parameters were applied to eliminate the influence of soil roughness in soil moisture inversion. The X-Bragg model was proposed on this basis to improve the disadvantages of the small perturbation method, the traditional soil moisture inversion model, which could not characterize the cross polarimetric and depolarization characterization^[102,103]. With the abundance of the full polarimetric data, more soil roughness characterization can be explored fully^[104,105].

The inversion of crop growth parameters using polarimetric parameters is also one of the hot issues in current research, and many research results have emerged in recent years. On the basis of Radarsat data, the research team of the Canadian Society of Agriculture and Food performed the inversion of multiple growth parameters and crop yield estimation with a variety of crops^[106-108]. The research group of the Shaoyun^[109,110] team of the Chinese Academy of Sciences also used full

Tab. 3 Summary of studies using polarimetric characterization

Application	Description of SAR parameters	Result	Reference
Crop classification and identification	Pauli decomposition parameter; Stokes vector feature; Decomposition parameter based on eigenvalue and eigenvector; Freeman-Durden, Yamaguchi decomposition parameter; Span-Pauli decomposition parameter, $H-\bar{A}-\alpha$ decomposition parameter; Cloude decomposition parameter	<ol style="list-style-type: none"> 1. Adding polarimetric features can effectively improve the classification accuracy. 2. For different crops, the difference is obvious. 3. The accuracy of crop classification can be effectively improved by adding temporal features of polarimetric features. 4. The classification accuracy of adding polarimetric decomposition feature is higher than that when only simple linear polarimetric combination is used. 5. The classification results using compact polarimetric features can achieve the same accuracy as the use of full polarimetric features. 	[3,65,66]
Inversion of farmland parameters (soil moisture/ground roughness)	<ol style="list-style-type: none"> 1. Parameters such as depolarization ratio, co-polarimetric correlation coefficient, coherence parameter, scattering entropy, and scattering angle were introduced to analyze the relationship between soil moisture and backscattering coefficient; 2. The parameters of polarimetric decomposition mainly include Freeman-Durden and eigenvalue decomposition 	<ol style="list-style-type: none"> 1. Using the multipolarimetric feature can better reduce the uncertainty of soil moisture inversion than using the single polarimetric feature and improve the inversion accuracy. 2. The inversion accuracy can be improved by using the parameters of polarimetric decomposition instead of backscattering coefficient. 3. With the introduction of polarimetric parameters, the inversion results are affected by crop phenology and crop types. 	[3,67]
Inversion of crop growth parameters	Polarimetric synthesis and polarimetric decomposition parameters; parameters were developed based on polarimetric synthesis and decomposition parameters, such as radar vegetation index and reference height parameters.	<ol style="list-style-type: none"> 1. Growth parameters include LAI, biomass, and crop height. 2. X- and C-bands are sensitive to the change in LAI. 3. Inversion results are affected by crop phenological period and crop type. 4. More accurate inversion of crop growth parameters can be obtained by using multipolarization synthesis and decomposition parameters (about 30 parameters have been used for crop growth parameters inversion at present) 	[80-83]
Division of crop phenological period	Cloude-Pottier decomposition parameters, polarimetric ratio, polarimetric difference ratio, polarimetric synthesis parameter (polarization degree), CP backscattering coefficient, and polarimetric decomposition parameter, Stokes parameter	<ol style="list-style-type: none"> 1. Time series data are mainly used to retrieve or monitor the phenological period. 2. The methods include classification and dynamic tracking. 3. The data used for monitoring include X - and C-band. 	[9,84-88]
Crop disaster monitoring	Polarimetric index (HH/VV, HH/HV surface scattering, Span, double scattering/ Span)	<ol style="list-style-type: none"> 1. Different polarizations have an obvious effect on lodging. 2. Both polarimetric entropy and polarimetric index can reflect the lodging. 3. The occurrence of lodging is accompanied by obvious changes in polarimetric scattering mechanism, so it can be characterized by polarimetric characterization. 	[89,90]

polarimetric and Compact Polarimetric (CP) data in studying the application of polarimetric characterization in crop growth monitoring and yield estimation. Jiao *et al.*^[106] and McNairn *et al.*^[107] confirmed the sensitivity of SAR polarimetric characterization to LAI by using polarimetric parameters (HV intensity, reference height, volume scattering component of polarimetric decomposition), and their research improved the performance of the traditional WCM, overcoming the limitation

of using backscatter to retrieve the low saturation point of LAI. They also demonstrated that LAI is an effective index for crop yield estimation. Wiseman *et al.*^[108] analyzed the response of C-band polarimetric parameters to dry biomass of corn, soybean, rape, and spring wheat comprehensively. They pointed out that the sensitivity of each polarimetric parameter to crops was affected by crop type and phenological period of growth, which also indicated the potential of po-

larimetric characterization in crop phenological monitoring. Zhang *et al.*^[111] demonstrated the potential of different polarimetric parameters in crop biomass, LAI, and plant height by extracting 27 simplified polarimetric parameters. However, most of the above studies used the direct relationship between the polarimetric parameters and crop growth parameters to invert the crop growth parameters, which have strong regional dependence. Some studies took advantage of the trade-off advantages of the semi-empirical model and applied the polarimetric characterization to WCM model to improve the accuracy and applicability of the inversion results^[112,113]. The application of SAR technology in the identification of phenological period used the advantage of polarimetric characterization to reflect the structural changes of crops throughout the growth period. First, the polarimetric characterization was extracted from the SAR polarimetric images covering the phenological period. Second, the change characteristics of the polarimetric parameters in the whole growth process of crops were analyzed, and then the appropriate polarimetric parameters were selected to divide each phenological period. Most such research used classification algorithms^[84,85]. To overcome the low robustness of the empirical threshold, some researchers developed dynamic modeling methods, such as Kalman filter and particle filter^[114,115]. Considering the impact of missing time series images in the phenological period of interest, some studies developed a method that combines alternative parameters and filtering methods to retrieve crop phenological periods^[86-88].

Yang *et al.*^[89] used polarimetric characterization to identify wheat lodging disasters. They found that the scattering energy of HH and VV polarization before and after wheat lodging had an obvious inversion phenomenon, and the characterization of multiple polarization combination parameters changed significantly before and after wheat lodging, thus providing a rationale for the use of polarimetric characterization in lodging monitoring.

The application of polarimetric SAR features further expands and deepens the application of

SAR information in agriculture. These results proved that polarimetric features have great potential in agricultural application, especially in crop identification, crop growth parameter inversion, and yield estimation, and may become one of the important tools for precision agriculture in the future.

3.3 Interferometric characterization of SAR

The purpose of interferometry is to obtain the elevation of terrain by using a simple phase elevation relationship ($\varphi = k_z h$). The traditional Interferometric SAR (InSAR) usually uses the single-band and single polarization mode, which does not consider the polarimetric characterization of scatterers. The features used include the interferometric phase and amplitude of single polarization. Polarimetric Interferometric SAR (PolInSAR) adds polarimetric features to the original interferometric amplitude and phase characterization, and it uses full polarimetric observation for interference processing. It also combines the sensitivity of interferometric features to spatial distribution and polarimetric characterization to the physical properties of scatterers. It can combine the fine structure features and spatial distribution features of targets to improve the performance of traditional interferometry. It can also distinguish the vertical distribution characterization of different scattering mechanisms in the same resolution unit^[116].

The application of InSAR features in vegetation is mainly based on the phase features obtained by interferometry, which include the phase features caused by vegetation offset. To analyze the influence of vegetation structure, PolInSAR is used to monitor the vegetation offset. These features were first used to estimate forest height according to the available features and vegetation scattering characterization, and forest height estimation methods based on geometric relationship and physical model were developed^[117]. The application of InSAR and PolInSAR features in agriculture mainly focuses on the crop height estimation. The temporal decorrelation of repeat-pass InSAR data seriously affects its application in vegetation coverage areas. For example, even if only a 24-hour time difference exists, ERS-1/2

TanDEM data are affected by temporal decorrelation. Nevertheless, the coherence of the data is obviously related to the height of various crops, which has great potential in crop height estimation^[118]. With the enrichment of PolInSAR data, some researchers proposed vegetation scattering models that were suitable for polarimetric InSAR data and could be used to retrieve vegetation parameters. The Random Volume over Ground (RVoG) and Orientation Volume over Ground (OVoG) models are the most widely used PolInSAR vegetation scattering models^[119]. The RV in the former means a random volume, that is, the attenuation coefficient of electromagnetic wave is independent of the polarization mode. The OV in the latter represents the oriented volume, that is, the attenuation coefficient is a function of polarization when the electromagnetic wave propagates in the vegetation^[120]. The RVoG and OVoG models are often used to retrieve vegetation height. Lopez-Sanchez^[121] first analyzed the feasibility and limitations of these two models in crop height inversion and found that the OVoG model could better describe the scattering characterization of crops. This finding was proven by experimental data showing that the OVoG model was feasible in retrieving the height of corn and rice. Research on crop height inversion based on airborne PolInSAR data was conducted gradually. The phase amplitude joint inversion method based on RVoG model was used to retrieve the height of rape, corn, wheat, barley, and sugar beet. The results showed that the RVoG model was crop type dependent. For example, the inversion heights of rape, corn, and sugar beet using this model were better, and the standard deviations were between 0.20 and 0.31 m. However, for wheat and oats, the standard deviation was 0.33 and 0.61, respectively. With the abundance of TerraSAR/TanDEM space-borne InSAR data, which have no temporal decorrelation, research on crop height inversion based on InSAR and PolInSAR has emerged in recent years. Erten *et al.*^[122] and Rossi *et al.*^[123] studied the phase changes of rice during its entire growth period. The information they obtained was used to analyze the rela-

tionship between interferometric phase and rice canopy height. The results confirmed that the choice of HH or VV polarization will significantly affect the results of rice height estimation. On the basis of the TerraSAR/TanDEM interferometric SAR data, Lee *et al.*^[124] proposed a method using the RVoG model and lookup table to retrieve the rice height, and the RMSE was around 0.10 m. Guo Xianyu *et al.*^[125] developed the RVoG model and used dual-polarized TerraSAR/TanDEM interferometric SAR data inverted rice height. When the rice plant is higher than 0.4 m, better estimation results can be obtained. The R^2 between the estimated value and the true value was 0.86, and RMSE was 6.79 cm.

The existing inversion results for different crop heights fully demonstrated the potential of interferometric and polarization interferometric features in the monitoring of crop vertical structure changes. However, due to the serious influence of temporal decorrelation, which resulted in great noise in the repeat-pass interferometric image in a crop-covered area, the inversion results were greatly affected, thus limiting their wide application. With the emergence of non-temporal decorrelation InSAR and PolInSAR data, interferometric and polarimetric interferometric SAR features can be used for crop vertical structure monitoring. Although some studies have been conducted, the potential of interferometric features in agricultural applications needs to be further explored.

3.4 Tomography features of SAR

Tomography SAR (TomoSAR) is proposed for vertical observation of ground objects. At present, two kinds of tomography techniques in SAR application are available. One is multi-baseline SAR tomography, that is, adding multiple interferometric antennas perpendicular to the line of sight to realize repeatable observation, which is equivalent to synthesizing a larger aperture perpendicular to the line of sight to obtain the height dimension, and the scattering value of the scene in the vertical direction is usually obtained by spectral analysis^[126-128]. The other is polarimetric coherence tomography, which uses the

interferometric coherence coefficients of different polarizations to retrieve the vertical structure distribution of a forest. This method involves reconstructing the equation between the backscattering profile and the height of the observation scene by using the interferometric coherence changes of different polarizations. Then, the vegetation height and terrain phase characteristics are obtained by using the observed coherent data, the obtained vegetation height, and terrain phase characteristics introduced into the vertical structure equation via Fourier-Legendre polynomial expansion, and the scattering values along the vertical direction of the scene are obtained by solving the coefficients^[126,128,129]. The imaging algorithms of multibaseline SAR tomography include three categories: nonparametric spectral estimation, parametric spectral estimation, and sparse spectral estimation. Sparse spectrum estimation method can effectively solve the drawbacks of interpolation method in SAR tomography due to the uneven distribution of the baseline and improve the efficiency of tomography SAR data processing. In recent years, many related imaging algorithms have been developed based on this method^[130,131]. Single-baseline polarimetric coherence tomography can only improve the depth of the volume scattering layer and the surface phase characterization of the mixed surface/volume scattering. The resolution of double baseline is higher than that of single baseline, but when the number of baselines is more than three, the method becomes less stable. In addition, the method needs to input prior knowledge, such as ground phase and vegetation height, which are obtained by PolInSAR technology. Therefore, it will underestimate the vegetation height, although it still depends on the development of PolInSAR technology^[129,131].

The application of TomoSAR is still in the initial stage of research. Additional applications of SAR tomography with focus on forest biomass retrieval and its application in agriculture have just begun^[131]. With the rapid growth of crops and the impact of complex environmental scenarios, most of the current research focuses on the inversion of

crop height parameters, the vertical backscattering changes at all frequencies during the crops' whole growth period, and the distinguishment of surface or volume scattering in crop-covered areas^[3,132-139]. During the early days of research in this field, researchers used indoor and outdoor ground-based radar experimental to study the three-dimensional scattering profiles of wheat and corn at X-, C-, and L-bands, and explored the influence of polarization mode, incidence angle, and frequency^[133-135]. With the emergence of airborne TomoSAR data, Pichierri et al. used airborne TomoSAR data to study the feasibility of its use in farmland scenes. On the basis of the OVoG model, Pichierri *et al.*^[139] analyzed the feasibility of X-, C-, and L-band inversion in wheat, oat, corn, and rape height retrieval by using dual-baseline polarimetric coherence tomography. The results demonstrated the influence of baseline length and frequency on different crop height retrieval: the sensitivity of polarimetric interferometric coherence to crop height was reduced when the baseline is small; the RMSE was about 10% when L-band was used for rape and corn height inversion; and the RMSE of X-band was less than 24% for height inversion of barley and wheat. Joerg *et al.*^[132] obtained the vertical backscatter profiles of maize, barley, and wheat at different growth stages at X-, C-, and L-bands by using Capon nonparametric spectral filtering method. From the acquired vertical section, we can see the obvious secondary scattering mechanism in the maize-covered area, the obvious surface scattering mechanism in the wheat canopy, and the obvious field ridge scattering effect in the wheat-covered area. The HH scattering characterization of barley is almost invisible. On the basis of the scattering profiles of different crops, the researchers further analyzed the feasibility and effective methods of separating bulk scattering and surface scattering mechanisms^[132,136-138]. The acquisition of time series TomoSAR data also significantly affects its in-depth application in agriculture because of the rapid change of crops during the whole growth cycle. These studies also showed the influence of temporal decorrelation on polarimetric interfero-

metric coherence tomography characterization in crop monitoring^[132,140].

TomoSAR features have great potential in improving the accuracy of crop classification, crop height, and biomass inversion. However, the application of these features in agriculture has not been fully explored yet. In the future, with the implementation of multibase station SAR observation technology and the implementation of a new SAR satellite plan, the application of TomoSAR features in agriculture needs to be further developed.

4 Summary and Prospect

4.1 Summary

Currently, active radar remote sensing technology has been applied in various fields of agriculture and has fetched substantial gain. However, in agricultural application, different organizations and individuals have different concerns with regard to agricultural information and the demand for radar technology application in agriculture. Despite several conclusions in various fields, concrete demands and further applications still need further exploration and development. For example, even though we have global-scale classification products, most of them focus on classification of the earth surface and lack accurate, subtle crop type classification. Moreover, most crop identification and classification-related research was conducted in homogeneous regions. Achieving the required accuracy in composite and complex farmlands is difficult. Taking precise farming as an example, we need more information about how to use land in particular demand and how to operate during the whole crop growth. Many agricultural disasters, especially floods, greatly affect crop yield. However, few relevant studies focus on flood monitoring by using radar data. The government, organizations, and individuals are currently paying more attention to yield estimation, but only a few reports focus on using radar technology to estimate yields. The SAR information that is used focuses more on backscattering coefficient with simple statistical methods. Some research has been conducted on

yield estimation by using assimilation methods, but the studies remain theoretical and have not been applied in large regions or composite farmland scenes.

The development of radar technology is a process of exploring and utilizing the resources of microwave and electromagnetic wave. The applications of radar characteristic in each field of agriculture are different. The most widely used characteristics are backscattering and polarization; the use of interferometry SAR, polarimetric interferometry SAR, and tomography SAR has just begun and needs to be further explored. The backscattering characteristic is widely used in the field of soil moisture and crop growth parameter inversion. Most growth parameter inversion studies used rice as the object, and the estimation method focused on empirical and semi-empirical models. These models are limited because the scattering mechanisms of different/same crops change at different growing stages obviously, thereby affecting the backscattering characteristic considerably. Moreover, the current empirical and semi-empirical models mostly use incoherent scattering models, in which the phase characterization of SAR data is not used. Most of the soil moisture inversion models are based on specific observation data, which show great uncertainty when applied in large areas. Phase characterization is also not effectively used. Polarization characterization is mostly utilized in crop identification/classification and crop growth parameter inversion. Current research is limited to homogeneous regions, and the classification is limited to crops that have a simple scattering mechanism. Only a few studies have begun to explore crops with a complex scattering mechanism. In research on crop growth parameter inversion with polarimetric decomposition characteristics, inversion results become more uncertain and less applicable because most of the inversion models assume that the crop canopy is composed of homogeneous scatter and thus cannot describe the complex scattering situation of crop canopy. In addition, the mechanism of crop growth and yield cannot be fully revealed because the hydrological, meteorological, environ-

mental, and other influencing factors in the crop growth process are rarely considered in crop yield estimation.

4.2 Prospect

Given its unique advantages, radar remote sensing plays an important role in agricultural remote sensing monitoring. The application of radar in agriculture has gradually developed from ground observation to airborne and space-borne observation through decades of development. The sensor has developed from the initial scatterometers to the present multifrequency, multipolarization, multiangle, multi-revisiting, and multidimensional SAR observation. At present, radar remote sensing has made much progress in many aspects of agriculture applications, including crop identification and classification, field parameter inversion, crop growth parameter inversion, and crop phenological period classification. However, research on crop disaster monitoring and crop yield estimation is still in the experimental stage, and most of the relevant technologies and the methods applied in them are still in the primary stage, which is why most of them have not been widely promoted in practical application. This situation occurred because of the following reasons. First, the development methods and models have some limitations that need to be further improved and developed. Second, few SAR data resources can support real-time agricultural monitoring. For example, most polarimetric interferometric SAR data and tomographic SAR data rely on foreign airborne and partial space-borne experimental data, thereby limiting the in-depth analysis and study of robust algorithms and models. For disaster monitoring, the microwave scattering mechanisms for disasters have not been fully explored, and related research has not started yet. For crop yield estimation, its accuracy depends on the accuracy of crop growth status monitoring, but research on the fusion of crop growth status information and SAR information is still in the preliminary stage. In current agricultural applications that use radar remote sensing technology, passive microwave remote sensing data can be an effective compensation due to its convenient acquisition, high temporal resolution, and simple

data processing. The application of radar technology in agriculture has shown great advantages and potential, becoming a more powerful way to promote the effectiveness and efficiency of the rapid development of precision agriculture and smart agriculture. With the increase in SAR data types and imaging modes, multidimensional SAR observation based on multifrequency, multipolarization, and multiangle is becoming even more possible. In the future, we should pay more attention to refining the relevant methods to meet the needs of relevant stakeholders, then promote the depth and effectiveness of the use of radar technology in the agricultural field.

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