三维极化成像和时间序列 SAR 森林特征探测

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组织开展了 2021 年根河市林区多维度 SAR、2022 年肇庆和 2023 年塞罕坝林区 P 波段 SAR 机载试验，获取了根河试验区的 P、L、S、C 和 X 共 5 个波段的极化 SAR 数据、P 波段重轨层析 SAR 数据和 C 波段双天线干涉 SAR 数据，以及肇庆和塞罕坝试验区的 P 波段重轨层析 SAR 数据。基于以上数据集，分析评价了 5 波段极化 SAR 数据及不同波段组合估测森林蓄积量的性能，评估了层析 SAR 技术在中国不同林区的应用效果。

在极化 SAR（PolSAR）辐射定标方面，采用星载 GF-3 数据和机载 UAVSAR 数据，提出了交叉共极化比系数，获取任意分布目标的极化散射真值，能够有效降低现有方法对目标的约束，解决了稳定目标提取和稳定目标统计信息有效利用等问题；在 PolSAR 地形辐射校正方面，发展了基于 RPC 模型的地形辐射校正（RTC）方法，降低了极化 SAR 几何和 RTC 的技术门槛；进一步提出了适用于极化 SAR 监督分类的 RTC 方法，可提高森林类型分类精度 20%左右。

采用星载 Radarsat-2 和机载 UAVSAR 时序极化 SAR 数据开展了一系列 PolSAR 分类方法研究。构建了时序-极化特征，反映了特征的变化程度，为有效实现特征选择奠定了基础；提出了极化维和时间维的特征选择算法 IESSM 和 SSV，并设计了基于 Transformer 的分类器，改善了特征冗余问题，增强了分类器对于时序极化 SAR 数据的适应性；基于时序极化 SAR 数据表征乘方模型，具有完整的矩阵性质，能够全面表征各种散射机制变化，为时序极化 SAR 数据的散射变化量提供了有效的矩阵基础，并且基于乘方模型提取了时变散射特征，增强了对于散射变化量的表达能力，提高了分类精度。

在干涉 SAR 方面，创新了适用于短波长干涉 SAR 的多层模型，通过实现干涉 SAR 相

干性观测量计算和理论模型服从相同假设提高森林高度的反演精度；提出了 P/X 双频干涉 SAR 差分测量森林高度和协同估测森林 AGB 的方法，提高了林区 DTM/DSM/CHM 和森林 AGB 的提取精度；在层析 SAR 方面，发展了 DEM 辅助的多基线干涉 SAR 的基线校正和相位补偿方法，改善了林区层析 SAR 的成像质量；提出了基于层析 SAR 剖面拟合的多特征协同的森林生物量估测方法，在热带雨林区域的森林生物量估测中达到了较高精度（>90%）。

目前大多数 TomoSAR 方法使用样本协方差矩阵的局部均值，可能会得到较差的谱优化效果，并丢失一些细节信息。此外，频谱不可避免地会产生副瓣效应。针对上述问题，采用非局部均值方法识别与目标像素相似度高的相邻像素，从而全面反映目标像素的特征信息；此外，在 TomoSAR 中引入了 G-Pisarenko 方法来减少干扰信号。分别用 BioSAR 2008 L 波段数据和 AfriSAR 2016 P 波段数据验证了这两种方法的可行性和有效性。此外，针对传统 TomoSAR 方法中由于高程离散导致的散射体定位误差，提出了一种基于原子范数最小化（ANM）的 TomoSAR 算法，该算法的性能已通过 TerraSAR-X 数据验证。另外，还发展了 DEM 辅助的多基线干涉 SAR 的基线校正和相位补偿方法，改善了林区层析 SAR 的成像质量；提出了基于层析 SAR 剖面拟合的多特征协同的森林生物量估测方法，在热带雨林区域的森林生物量估测中达到了较高精度（>90%）。

PolTomoSAR 技术已经发展到在 P 波段使用自适应参数信号处理方法来表征热带森林，在 L 波段使用最少数量的图像来表征温带森林。根据不同的森林特征和不同的时相情景，通过计算卫星发射任务的最终性能局限，对协同利用 BIOMASS 卫星不同模式数据的价值进行了评价。对外部信息源（如 GEDI）可能带来的增益，已通过将该估计与贝叶斯原理耦合进行了评估。利用森林垂直剖面模拟模型模拟剖面的和实际剖面可能有较大不同，对这种情况可能产生的问题进行了研究。一些已研发的技术将有助于 BIOMASS 处理方法组的多任务算法和分析平台（MAAP）的开发。在 BOMASS 三级产品加工链（即森林高度、地上生物量和森林扰动）的定义方面，我们也做了一些工作。

哨兵 1 号的时间序列测量被用于绘制大规模的森林砍伐地图(见 https://www.tropisco.org/)，基于贝叶斯处理的新技术正在开发中。发展了一种新的可近实时在线检测森林损失的技术，相比于现有可业务运行的方法，比如全球森林观察采用的方法，在亚马逊森林和巴西塞拉多草原上获得了非常好的结果。

CHARACTERIZATION OF VEGETATED AREAS USING TIME-SERIES OF POLARIMETRIC SAR DATA AND TOMOGRAPHIC PROCESSING

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The airborne multi-dimensional SAR flight experiment in the forest area of Genhe district was organized in 2021, and the PolSAR dataset of P, L, S, C and X bands, P-band TomoSAR dataset and dual antenna InSAR dataset of C band were obtained. The P-band SAR flight experiment in the forest area of Zhaoqing and SaiHanBa were organized in 2022 and 2023, and the P-band TomoSAR dataset were obtained. Based on above dataset, we analyzed and evaluated the performance of PolSAR data of 5 bands and different band combinations in estimating forest volume, and evaluated the application effect of TomoSAR technology in different forest areas of China.

In the case of PolSAR data radiometric calibration method development, using space-borne GF-3 data and airborne UAVSAR data, we proposed the cross-co-polarization radio coefficient, which can be used to obtain the truth value of polarization scattering of any distributed targets. The calibration method can effectively reduce the constraints on targets of existing methods. In case of terrain radiometric correction (RTC), one RTC method for PolSAR based on RPC model has been proposed, which reduces the technical threshold for geometric and radiometric correction of PolSAR. In addition, a RTC method suitable for supervised classification of PolSAR was proposed, which can improve the accuracy of forest type classification by about 20%.

A series of land cover classification method studies were carried out using spaceborne Radarsat-2 and airborne UAVSAR time-series polarimetric SAR data. We constructed the time-polarization features, reflected the degree of feature variance, and constructed the foundation for effective feature selection; proposed the polarimetric and time dimension feature selection algorithms IESSM and SSV, designed a classifier based on Transformer, and reduced the feature redundancy and enhanced the adaptability of the classifier. We constructed a data representation power model, which can maintain a complete matrix property and fully represent the changes of various scattering mechanisms, providing an effective matrix basis for the scattering changes of multi-temporal PolSAR data; extracted the time-variant scattering features based on the proposed power model, enhanced the expression ability of scattering variation, and improved the classification accuracy.

In terms of InSAR, the multi-layer model suitable for short wavelength InSAR is innovated, and the retrieval accuracy of forest height is improved by realizing that the observation calculation and theoretical model of InSAR coherence obey the same assumption. Moreover, the algorithm for jointly measuring forest height and forest AGB using P/X dual-frequency InSAR has been proposed, which effectively improves the extraction accuracy of DTM/DSM/CHM and AGB in forest areas.

Most current TomoSAR methods use a local means value of the sample covariance matrix, which may get the poorly refined spectrum, and lose some detailed information. In addition, the spectrum will inevitably produce sidelobe effects. To address the above issues, a non-local means method is applied to identify neighboring pixels with high similarity to the target pixel, thereby comprehensively reflecting its feature information. Moreover, G-Pisarenko method is introduced in TomoSAR to reduce the spurious interference signal. These two methods have been respectively verified that the feasibility and effectiveness with BioSAR 2008 L-band data and AfriSAR 2016 P-band datasets, respectively. In addition, we propose a TomoSAR algorithm based on atomic norm minimization(ANM) to solve the scatterer location error caused by elevation discretization in traditional TomoSAR methods. The performance of the algorithm has been verified by TerraSAR-X data. TomoSAR baseline correction and phase compensation methods for multi baseline interferometric SAR assisted by DEM have been developed, improving the imaging quality of TomoSAR over forested areas. Additionally, we have developed a multi feature collaborative forest biomass estimation method based on TomoSAR profile fitting, which has achieved high accuracy (>90%) in tropical rainforest regions.

PolTomoSAR techniques have been developed to characterize tropical forests at P band using adaptive parametric signal processing approaches, and over temperate forests at L band using a minimal number of images. The benefits of a synergistic use of the different modes of the upcoming BIOMASS missions have been evaluated by computing the ultimate performance limits of this mission for different forest characteristics, and according to various temporal scenarios. The gain provided by external sources of information, such as GEDI, has been evaluated by coupling this estimation with Bayesian principles. The case of estimation techniques using models of forest vertical profiles that differ from actual ones has been investigated. Some of the developed techniques will contribute to the BIOMASS processing group of methods Multi-Mission Algorithm and Analysis Platform (MAAP). Some work also been done regarding the definition of BOMASS level 3 product processing chain, i.e. Forest Height, Above Ground Biomass and Forest Disturbance.

Times series of Sentinel 1 measurements were used for mapping deforestation at large scale (see https://www.tropisco.org/) and new techniques, based on Bayesian processing are being developed. A novel near-real time online forest loss detection technique allowed to reach very good results, compared with operational existing methods, such as Global Forest Watch, over both Amazonian forests and Savannah such as Cerrado, in Brazil.