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空间目标在轨状态雷达成像估计技术综述(中文/English)

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摘　要：空间目标状态估计旨在获取目标在轨姿态运动和几何结构等状态参数，是完成目标动作意图分析、排查潜在故障威胁和预判在轨态势等任务的关键技术。通过雷达光电成像信息处理实现在轨姿态估计是空间目标状态分析的重要途径，当前已经形成了一系列代表性实用方法。该文首先简要介绍了国内外用于空间目标监测的地基逆合成孔径雷达发展现状；重点针对空间目标时序特征匹配、三维成像重建和多视融合姿态估计多类代表性方法进行原理介绍与技术总结：数据特征匹配的状态估计性能可靠但依赖目标模型先验；三维几何重建的状态估计具备目标精细刻画潜力但观测几何要求高。同时，该文也对空间目标在轨状态估计方向未来发展趋势进行了展望。

关键词：空间态势感知；逆合成孔径雷达成像；多源特征融合；目标姿态估计

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Review of On-orbit State Estimation of Space Targets with Radar Imagery (in English)

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Abstract: Space target state estimation aims to obtain a target's on-orbit attitude, structure, movement, and other parameters accurately. This process helps observers analyze the target action intention, check for potential fault threats, and predict the development of on-orbit situations and is the core technology in the field of space situation awareness. Currently, the estimation of the on-orbit state of space targets mainly relies on external observations from high-performance sensors, such as radars, paralleled by the emergence of a series of representative methods. This paper briefly introduces the development status of inverse synthetic-aperture radar used for space target monitoring at home and abroad. Then, several representative methods, including data feature matching, three-dimensional (3D) imaging reconstruction, and multi-look fusion estimation, are introduced. The data feature-matching technology performs well when the priori target 3D model and scene

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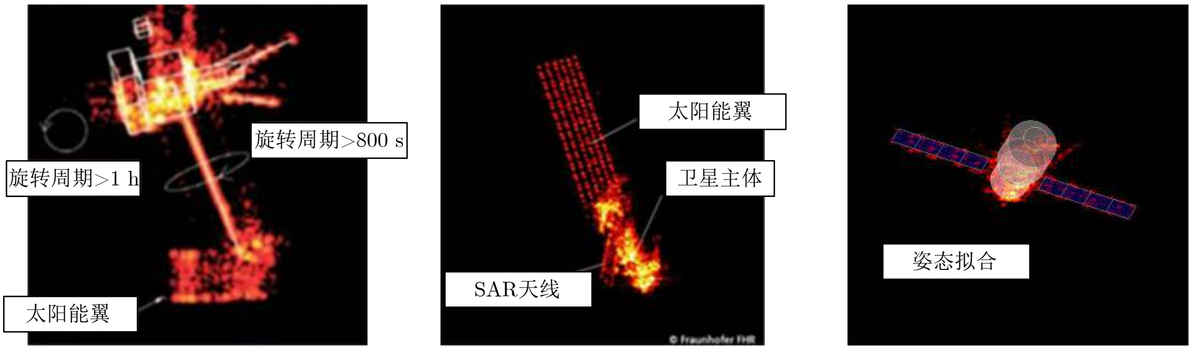
conditions are given. The state estimation with 3D geometric reconstruction has the potential for fine description of the target, but high-level observation conditions are required. Finally, the future development trend of this direction is forecasted.

Key words: Space situation awareness; Inverse Synthetic Aperture Radar imaging; Multi-sensor data fusion; Target state estimation

1 引言

随着航天技术的迅猛发展，世界各国加速对空间资源的开发建设，越来越多搭载高性能传感设备的空间目标被送入地球轨道，为军事侦察、实时通讯、资源勘探等航天活动提供重要信息。截至2021年4月累积超过36,000个人造目标被送入太空，其中超过22,000个目标仍处于在轨运行状态[1]。随着以SpaceX公司“星链(Starlink)”计划为首的商业航天活动兴起，这一数字将持续上涨，空间轨道资源将被进一步压缩，目标间相互影响的风险系数不断增大，空间态势安全面临极大挑战。2009年2月，美国商业卫星“铱33”与俄罗斯军用卫星“宇宙2251”发生了首次人造卫星相撞事件，碰撞所产生的碎片对其他临近目标构成了极大威胁[2,3]。因而，对在轨空间目标进行连续跟踪监测，进而分析其运行状态是当前空间态势感知领域的迫切需求。

空间目标在轨状态信息的分析通常依赖传感器的高质量追踪观测。长期以来，各航天大国都在积极研发光电、红外等高性能观测设备[4–16]。其中，具备远距离、高分辨探测能力，同时具有全天时、全天候、主动式特点的地基逆合成孔径雷达(Inverse Synthetic Aperture Radar, ISAR)是目前执行该任务的中坚力量。早在1970年，美国MIT林肯实验室根据Lincoln C波段ISAR成像雷达ALCOR实现苏联Salyut-1空间站、美国Skylab空间站等近地目标的高分辨成像与状态监测[8,9]。相关工作成果极大地推动了空间目标监测技术的发展[10,11]。MIT林肯实验室另一部Haystack雷达经过数十年的升级改造，工作波段已达W波段(96 GHz)，带宽拓展已至8 GHz，作用距离超过4×10^4 km，是现役最高分辨率的地基ISAR空间目标成像雷达。该雷达与HAX雷达以及距其实验场32 km处的多部宽带雷达组成了林肯空间监视组合网[12]，融入了美国导弹防御、空间态势感知体系。德国宇航局弗劳恩霍夫高频物理与雷达技术研究所的跟踪和成像雷达TIRA是欧洲航天局(European Space Agency, ESA)获取低轨卫星态势的重要途径，在一系列空间观测活动中提供了高分辨的空间目标成像结果[13–15]，如图1所示。该系统天线可实现方位360°、俯仰90°的全空域扫描，且其方位维度360°环扫仅需15 s。此外，法国太空监视雷达GRAVES、俄罗斯Voronezh雷达也是其他航天大国执行空间目标态势感知任务的主要地基雷达设备。我国空间观测ISAR设备研制与体系建设虽起步较晚但发展迅猛。1993年，第1台地基ISAR系统由航天二院23所研制完成并投入使用。近几十年来，中国电子科技集团、中国航天科工集团下属各研究所、中国科学院、西安电子科技大学、国防科技大学、清华大学、北京理工大学等高校对空间观测雷达体系开展了全方位的研究。目前，我国已初步建成了空间观测雷达体系，具备一定的空间目标跟踪、识别、监测能力。2018年4月对天宫一号“再入轨”的成功监测标志着我国空间态势感知体系建设已迈入面向应用需求的新阶段[16]。



(a) Adeos卫星ISAR图像
(a) ISAR imaging result of Adeos

(b) Envisat卫星ISAR图像
(b) ISAR imaging result of Envisat

(c) TG-I卫星ISAR图像
(c) ISAR imaging result of TG-I

图 1 TIRA空间目标成像观测结果[13–15]

Fig. 1 ISAR imaging result of three space targets by TIRA system[13–15]

综观地基雷达设备建设及空间目标状态监测技术发展，空间目标ISAR成像探测研究重点已从高分辨追踪成像逐步转移至目标成像信息参数化获取上，期望在高分辨ISAR图像中精确获取空间目标形状、尺寸、散射机理等关键信息，为空间环境态势研判、卫星运行状态调整、复杂空间协同活动提供技术支持。本文将根据现有空间雷达成像目标在轨状态估计方法特点，从数据特征关联匹配、三维成像重建测姿和目标状态自估计3条典型技术途径综述该方向先进技术方法，同时对该方向未来发展进行展望。

2　数据特征关联匹配技术

针对外部传感设备观测空间目标场景，一类经典目标状态估计方法通过计算机仿真模拟或实测数据长期累积的方式建立目标多类状态下的观测样本集合，而后根据当前观测样本在历史数据集合内最为相近的匹配结果确定目标状态参数。现阶段，该方向工作主要基于一维的激光反射单元相对位置、雷达散射截面(Radar Cross Section, RCS)序列变化特征和二维的雷达成像形态特征开展，并在国内外一些重要空间活动中得到了应用，具体介绍如下。

2.1　一维相对位置特征匹配估计方法

通过激光传感器测量空间目标配备的角锥反射器(Corner Cubere Reflector, CCR)距离变化定目标在轨运行状态是一类常见的数据特征关联匹配方法[17–20]。2013年至2015年，国际激光测距协会(International Laser Ranging Service, ILRS)曾组织全球各激光观测站点对失联的环境资源卫星Envisat进行长达两年的追踪测量。如图2所示，根据ESA公布的Envisat卫星结构，该卫星搭载了由9个CCR组成的后向反射矩阵单元(Retroreflector Array, RRA)。韩国天文学和空间科学研究所的Kucharski、奥地利理工学院的Kirchner等人[17]根据该单元在卫星整体内相对位置变化获得其姿态、运动参数，并进行长时间状态的拟合与统计，如图3、图4所示。该方法在Kirchner等人[18]先前关于Ajisai在轨自旋运动分析的研究中已有体现，并在后续其他研究团队关于Envisat运行状态受重力梯度影响的研究中得到进一步应用[19,20]。

与CCR一维相对距离测量类似，地基雷达测量获取的RCS序列特征也被用于空间目标在轨状态的参数估计。西安卫星测量中心的钟卫军等人[21]提出通过目标实际测量RCS序列与预先电磁仿真生成的RCS仿真序列进行特征匹配，采用混合粒子群优化(Hybrid Particle Swarm Optimization, HPSO)算法来实现三轴稳定目标在轨参数的优化求解。地面雷达站点RCS测量示意图如图5所示，目标RCS实际测量与仿真对比结果如图6所示。南京大学的吕江涛等人[22]在此基础上对目标在轨自旋情况下的姿态估计进行进一步拓展。

2.2　二维雷达成像特征匹配估计方法

MIT林肯实验室较早开展了利用空间目标雷达图像获取目标的几何拓扑结构特征的研究，并通过语义网络实现目标建模和数据积累建库，实现面向空间态势感知应用的目标分类识别。斯坦福大学的D’Amico等人[23]提出对比分析目标3D模型与其星载雷达图像间视觉特征进行目标在轨状态的判定，如图7所示。并在后续工作提出通过仿真生成目标ISAR图像获取其轮廓和边界信息，并用傅里叶描述子将这些信息特征化从而建立基于相似度衡量的目标分类识别模型[24,25]。

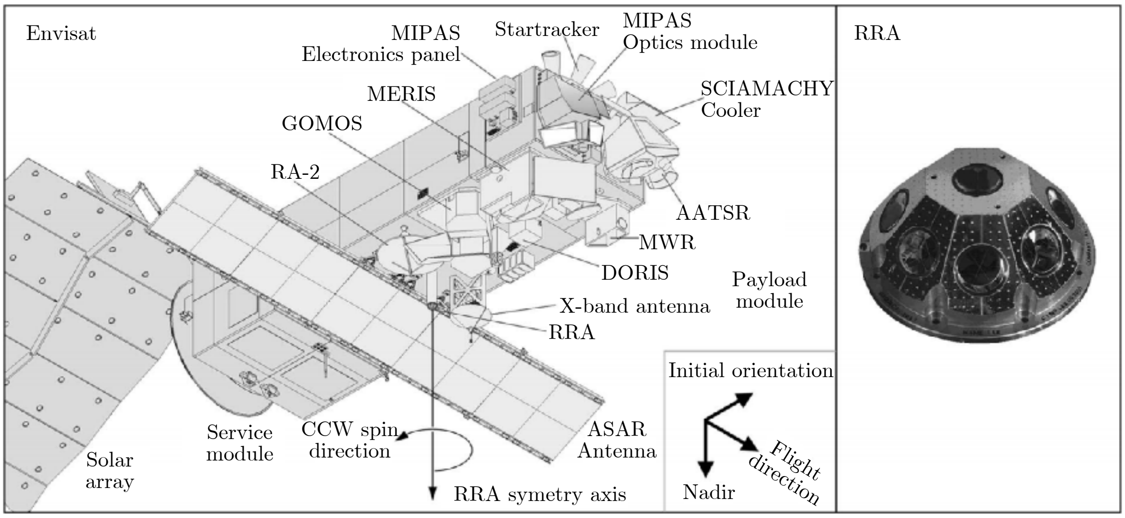
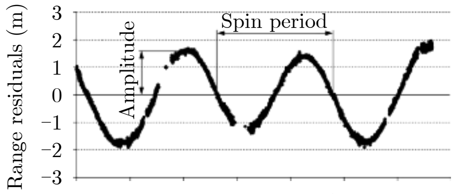


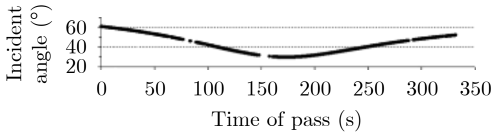
图 2 Envisat与其搭载的RRA结构模型(@ESA)

Fig. 2　Envisat and its RRA courtesy of ESA

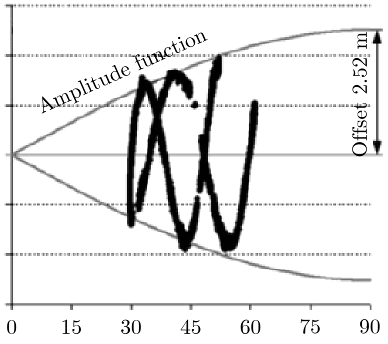
欧空局的Lemmens等人[26]结合TIRA雷达系统特点对合作目标建立仿真图像数据库，通过实测图像目标轮廓信息在数据库内匹配搜索来确定其在轨姿态参数。该团队基于该思路设计了一套工程化软件系统，如图8所示，应用于Envisat等卫星实际状态监测工作，并在后续研究中对精度影响因素进行讨论[27]。西班牙GMV宇航公司的Avilés等人[28]则在目标ISAR图像特征匹配的基础上，实现目标状态自动化测量，如图9所示。此外，福建农林大学的杨长才等人[29]提出利用目标主体主轴方向和太阳能帆板的姿态空间约束关系，通过连续观测图像序列间变化特征匹配搜索实现目标姿态估计。



(a) CCR相对位置变化
(a) Distribution of range residuals



(b) 镭射测量视角与反射器对称轴入射夹角变化
(b) Incident angle between the laser vector and the symmetry axis of the retroreflector panel



(c) 幅值变化拟合结果(A=2.52 sin(入射角))
(c) Representation of the amplitude function (A=2.52 sin(incidentangle))

图 3 2013年7月Graz站点Envisat卫星CCR相对位置变化测量结果[17]

Fig. 3 Range residuals calculated for Envisat pass measured by Graz SLR station on July, 2013[17]

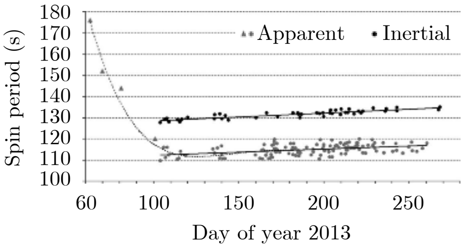


图 4 2013年Envisat自旋周期变化趋势分析[17](黑点为目标真实自旋周期；灰点为Graz站观测得到的CCR自旋周期)

Fig. 4 Spin period analysis of Envisat during year 2013[17] (black points Inertial spin period) and (gray points apparent spin period)

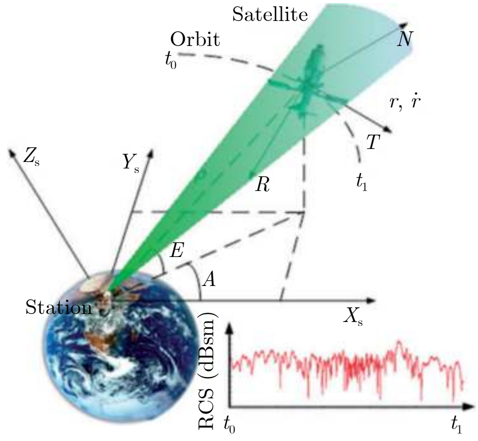
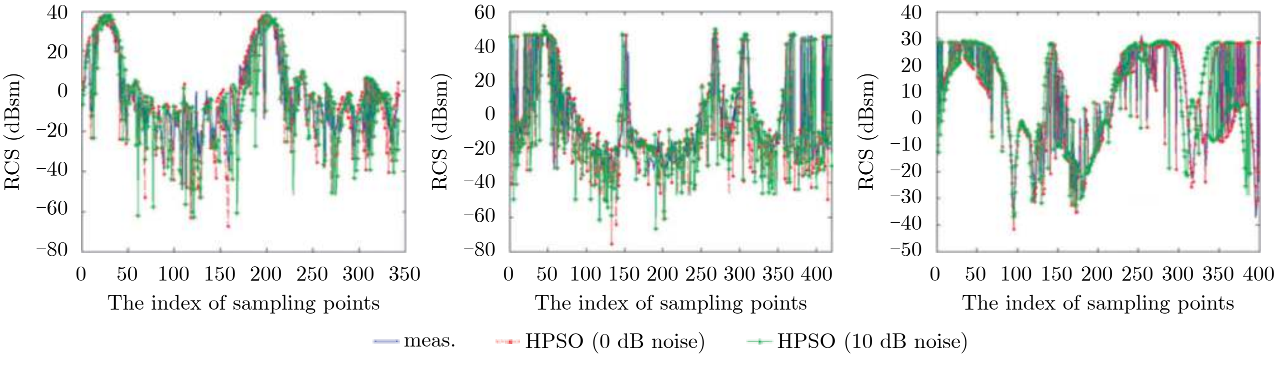


图 5 空间目标地基雷达RCS测量观测几何

Fig. 5 RCS measuring geometry configuration of space targets via ground-based radar



(a) 站点1观测数据
(a) The RCS sequences of station 1

(b) 站点2观测数据
(b) The RCS sequences of station 2

(c) 站点3观测数据
(c) The RCS sequences of station 3

图 6 实测RCS序列与角度优化后RCS模板仿真结果对比[21]

Fig. 6 Comparison between the measured RCS sequences and the RCS sequences[21]

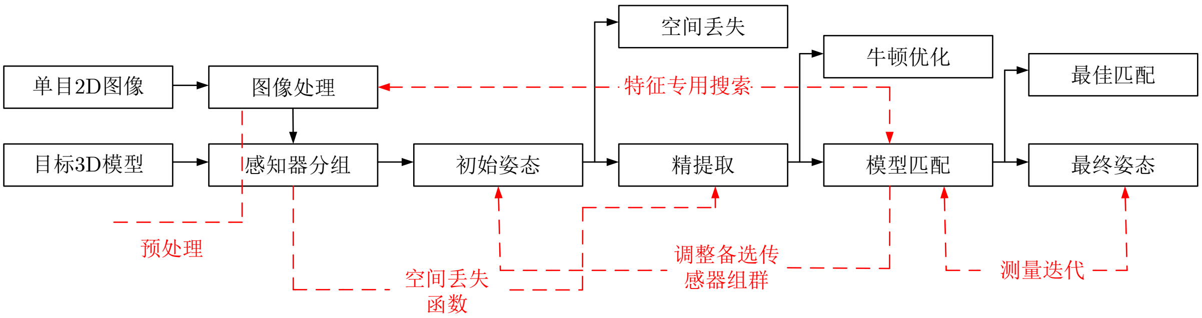
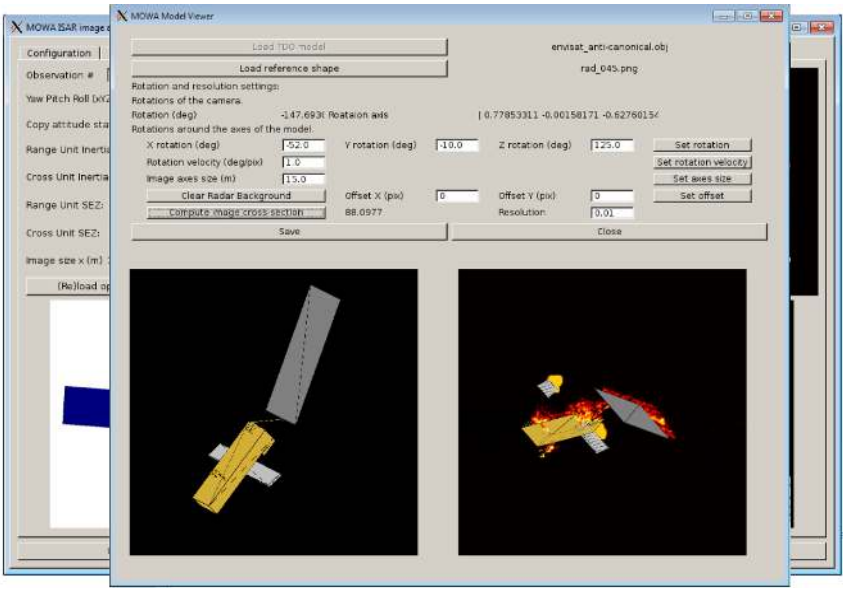


图 7 文献[23]中的目标姿态估计流程

Fig. 7 The flowchart of attitude estimation method in Ref. [23]



envisat_anti-canonical.obj
rad_045.png
Rotation and resolution settings:
Rotations of the camera.
Rotation (deg) -147.693(Roataion axis [0.77853311 -0.00158171 -0.6276015‹
Rotations around the axes of the model.
X rotation (deg) -52.0 Y rotation (deg) -10.0 Z rotation (deg) 125.0
Rotation velocity (deg/pix) 1.0
Image axes size (m) 15.0
Offset X (pix) 0 Offset Y (pix) 0
88.0977 Resolution 0.01

图 8 MOWA目标姿态拟合软件处理界面[27]

Fig. 8 Graphical interface of MOWA target attitude fitting[27]

总体而言，在处理观测积累数据样本充分的情况下，数据特征关联匹配技术可以完成对空间目标在轨姿态等状态参数的有效估计。对于合作式目标的长期监测，这类方法处理过程相对简便，因而应用广泛。但值得注意的是，该类方法难以适用于无法预先获取目标模型以及观测数据积累有限的非合作目标观测场景。

3　三维成像重建测姿技术

三维成像重建测姿技术着眼于地基ISAR成像几何建模，推导图像内目标结构形态与其真实三维空间分布间或直接或间接的数学表达，反演目标在轨状态参数。该类方法建立的物理模型一定程度上与计算机视觉领域研究相近，部分工作在雷达信息处理过程中借鉴了光学图像解译的成熟思路，亦为微波视觉领域研究提供了新视角[30,31]。

3.1 散射历史矩阵分解重建技术

使用矩阵奇异值分解(Singular Value Decompose, SVD)进行目标三维信息反演是一类常见手段，该类方法也常被称为“因式分解(Factorization Method, FA)”算法。该类算法主要借鉴了计算机视觉领域经典的“运动恢复结构”(Structure From Motion, SFM)方法[32,33]，使用SVD算法对空间目标雷达散射点观测矩阵(如距离-多普勒历史矩阵)进行分解，根据分解得到的结构矩阵与测量矩阵推算目标在三维空间内的形状、位置信息。1992年，康奈尔大学的Tomasi等人[34]根据光学相机透视成像特性，提出利用刚体目标在正投影下光流影(Image Stream)的形状与运动间联系恢复目标的三维结构信息。2009年，美国空军研究实验室的Ferrara等人[35]首次将该思路借鉴至雷达图像处理领域，利用矩阵因式分解的方式从雷达测量的目标散射点一维斜距矩阵中恢复各散射点在真实三维空间内的结构信息，如图10所示，并在该团队后续研究中引入目标特征级的先验信息以提升算法的鲁棒性[36]。

此后，澳大利亚通用动力先进信息系统公司的

图 9 空间约束下的Envisat序列姿态关联估计[28]

Fig. 9 Attitude estimation for Envisat sequence frames after constraining the search space[28]

McFadden[37]将因式分解方法推广至雷达成像二维观测场景下，根据各散射点在ISAR图像序列的二维坐标信息计算其真实三维空间坐标，并在舰船目标实测数据上进行验证，如图11所示。复旦大学的王峰等人[38,39]将该方法应用至稀疏成像场景，结合压缩感知(Compressed Sensing, CS)技术将多角度稀疏ISAR图像目标散射点序列分解，而后完成目标的三维重建，如图12所示。

需要指出的是，由于雷达、光学成像机理不尽相同，很难直接采用光学相机标定的方式对目标ISAR测量矩阵进行分析，进而导致了目标态势分析结果仅停留在目标结构分析阶段，通过因式分解方法获取散射点的位置信息仍需要额外的旋转矩阵标定。此外，该类方法一般基于多视角图像内目标关键点准确关联的前提假设。而在实际空间目标在轨姿态测量应用场景下，如何解决因观测视角变化引起目标ISAR散射点特征在长时间ISAR观测序列内的起伏问题，即“角闪烁”现象(Angular Glint Phenomenon)[40,41]，是该类方法亟待突破的一个技术难点。

3.2 多通道ISAR干涉三维成像技术

合成孔径雷达成像技术问世后不久，在其基础上发展的干涉合成孔径三维成像技术得到了各国研究机构和工业部门的广泛研究[42–44]。该技术利用多通道或者多航过的方式获取观测目标上不同散射点在高程维度的差异，根据配准后两幅二维雷达图像的相位差恢复各散射点的三维信息，广泛应用于星载SAR平台对地测绘、灾害监测等方向。随着地基ISAR装备的发展，干涉测量技术也被用于舰船目标、空间目标的识别与观测应用中。如图13所示，

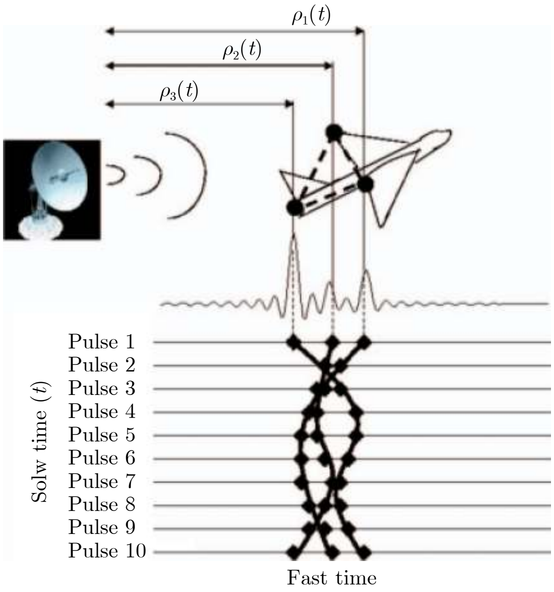


图 10 目标散射点雷达一维距离序列录取示意图[35]

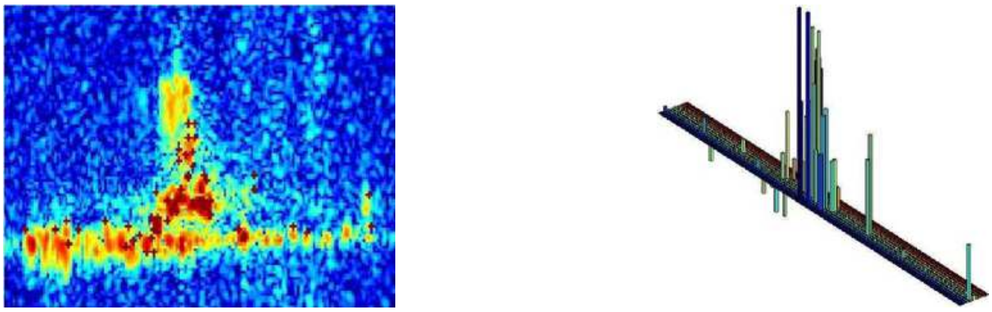
Fig. 10 Recording the distance sequence of target scattering points through radar ranging[35]

美国MIT林肯实验室使用由Haystack, HAX雷达及其他分布式接收站点组成的空间监视组合网系统对低轨道空间目标进行InISAR(Interferometric ISAR)测量[45,46]，其实验结果如图14所示。

北京理工大学的赵莉芝等人[47]针对双基观测场景讨论了十字形、L形天线的配置，并详细分析了水平、垂直基线长度对散射体三维位置估计精度的影响。该团队后续亦针对空间目标观测场景提出不同观测弧段间的三维干涉成像方法[48]。西安电子科技大学的邵帅等人[49]结合稀疏观测场景，提出利用Bayesian压缩感知方法实现多通道ISAR成像空变误差的高精度补偿，提升多通道InISAR三维成像效果及抗噪稳定性，并在实测Yake-42飞机数据上得到验证，如图15所示。对于空间目标在轨姿态测量应用，InISAR三维成像结果可以提供给定坐标系下的目标瞬时三维点云模型，并在此基础上应用点云分析方法可获取三维点云内目标姿态等状态参数。但受地基空间目标InISAR设备基线长度、人造目标散射点干涉相位处理方法等的限制，如何获取高精度空间目标稠密点云仍是当前该方向研究的一大难题。

3.3 雷达投影成像结构反演技术

通过建立目标在轨状态与其ISAR图像特征间数学表达进行空间目标状态参数估计是本领域另一个重要发展方向。2001年，MIT林肯实验室的Mayhan等人[50]结合几何衍射理论(Geometrical



(a) 实测ISAR图像散射点提取结果
(a) The extraction of the scattering points in the measured ISAR image

(b) 舰船目标三维重建结果
(b) The 3D reconstruction result of the ship

图 11 舰船目标散射点三维重建结果[37]

Fig. 11 The scattering points reconstruction result of the ship[37]

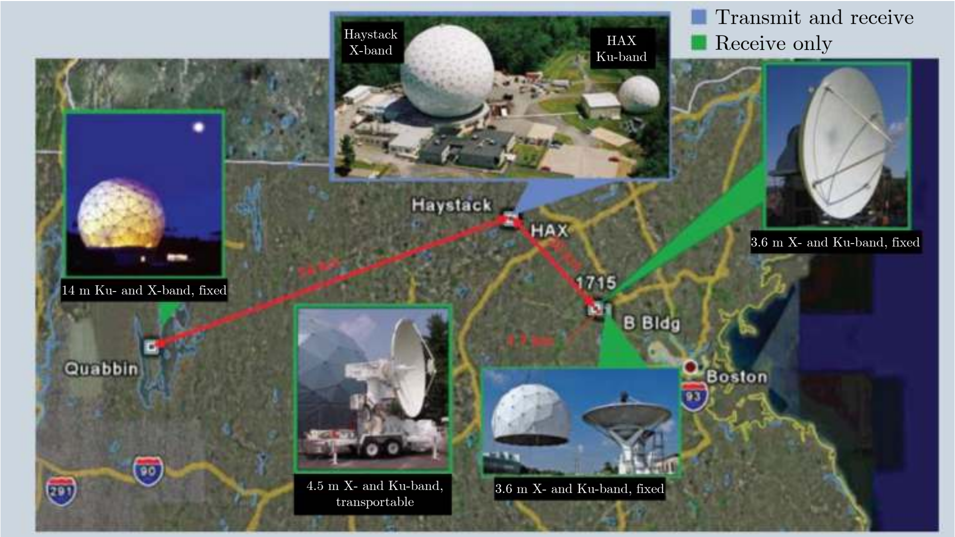
(a) 实测ISAR图像序列
(a) The measured ISAR sequence

(b) 目标三维模型
(b) The 3D model of the shuttle

(c) 目标三维重建结果
(c) The 3D reconstruction result of the shuttle

图 12 稀疏观测条件下航天飞机三维重建结果[38]

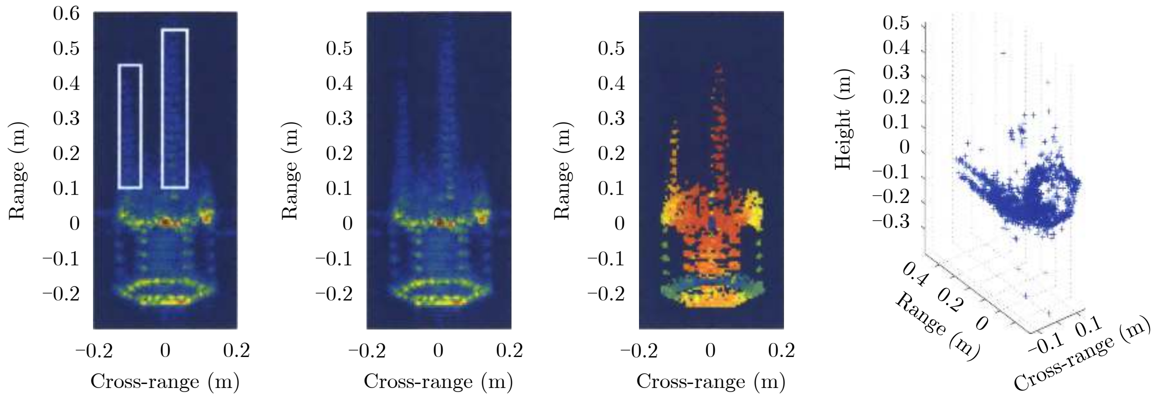
Fig. 12 The reconstruction result of shuttle in sparse observation[38]



A sparse aperture radar test bed has been established to conduct research on bistatic radar for space surveillance applications. Illumination is provided by the Haystack and HAX radars, and receive antennas are distributed across Massachusetts.

图 13 美国MIT林肯实验室空间目标InISAR测量系统[45]

Fig. 13 The InISAR measuring system for space targets in MIT Lab[45]



(a) 通道1
(a) Channel 1

(b) 通道2
(b) Channel 2

(c) 相差图
(c) Phase difference map

(d) 重建结果
(d) Reconstruction results

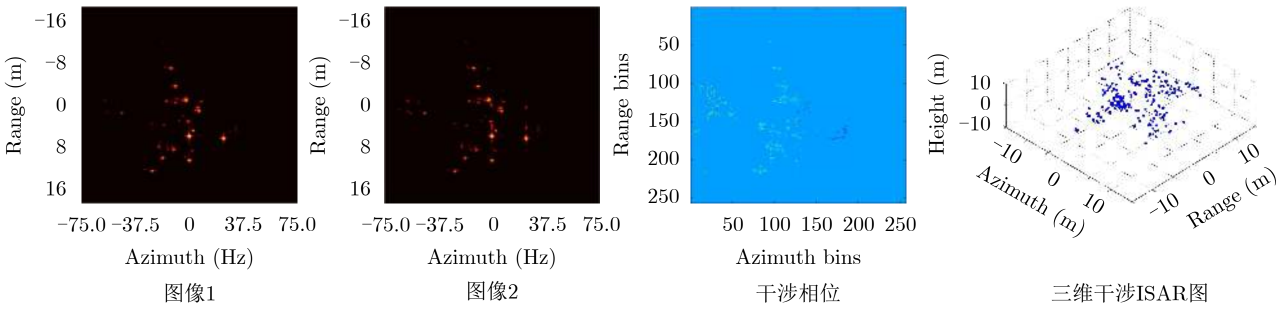
图 14 SPASE卫星三维干涉过程[46]

Fig. 14 The InISAR processing of SPASE satellite[46]

Theory of Diffraction, GTD)提出目标ISAR成像过程可理解为目标三维散射点在二维雷达成像平面上的垂直投影变换。如图16所示，空间目标地基ISAR成像观测过程可以使用目标本体坐标系下维度为2×3 的投影矩阵$\boldsymbol{A}$进行描述。在此基础上，西安电子科技大学的张磊、周叶剑等人[51]建立了目标三轴稳定情况下的在轨姿态参数及其典型矩形部件在ISAR观测图像序列内投影形态间的显式表达，并根据序列内部件结构平行四边形特征连续变化规律求解目标在轨姿态参数。图17中，根据目标姿态估计结果可在给定观测视角内重建观测图像序列，进而与原始图像序列进行视觉对比定性验证了估计结果的可靠性。

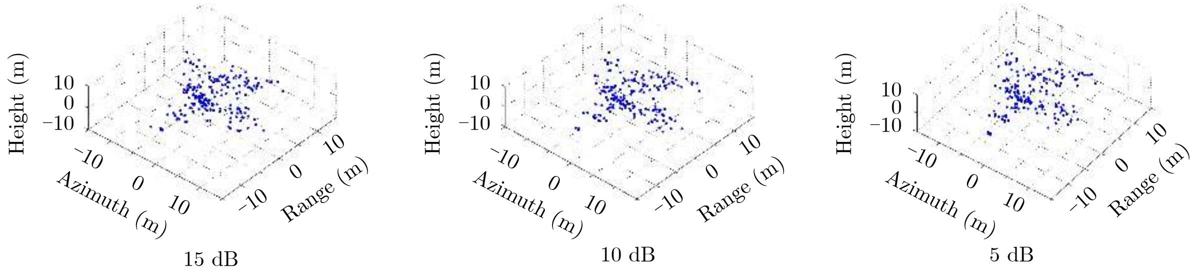
在此基础上，国防科技大学的王志会等人[52]提出结合ISAR成像投影模型，根据空间目标在ISAR观测图像序列内的线结构差分投影特征进行目标在轨姿态参数优化估计。中山大学的谢鹏飞等人[53]提出基于关键点提取的空间目标姿态自动化估计方法，首次将深度学习技术应用于空间目标ISAR图像特征的提取，通过关键点估计网络(Key Point Extraction Network, KPEN)从ISAR图像序列中提取目标关键结构点，实现空间目标姿态和部件尺寸的自动化估计，并在电磁仿真ISAR图像序列中得到了验证，如图18所示。

此外，为解决失稳目标瞬时姿态估计问题，西安电子科技大学的张磊、周叶剑等人[54,55]在后续研究中引入多站地基ISAR同步观测、同站雷达-光学异视观测模式，以此解决因目标在轨自旋带来的



(a) 实测飞机目标的三维干涉ISAR成像结果

(a) The InISAR 3D imaging of the measured plane target



(b) 不同信噪比下三维成像效果

(b) The performance of 3D imaging in different SNR conditions

图 15 Yake-42干涉ISAR三维成像结果[49]

Fig. 15　The InISAR 3D imaging result of Yake-42[49]

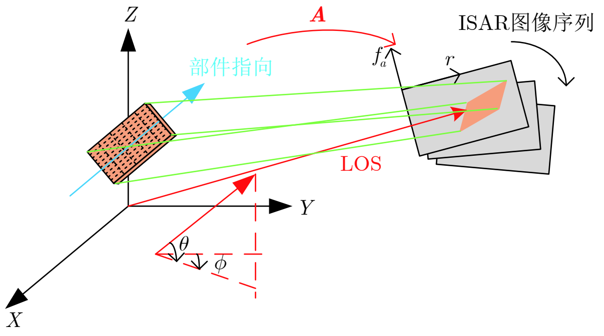


图 16 ISAR投影成像模型

Fig. 16　The geometrical model of ISAR projection imaging

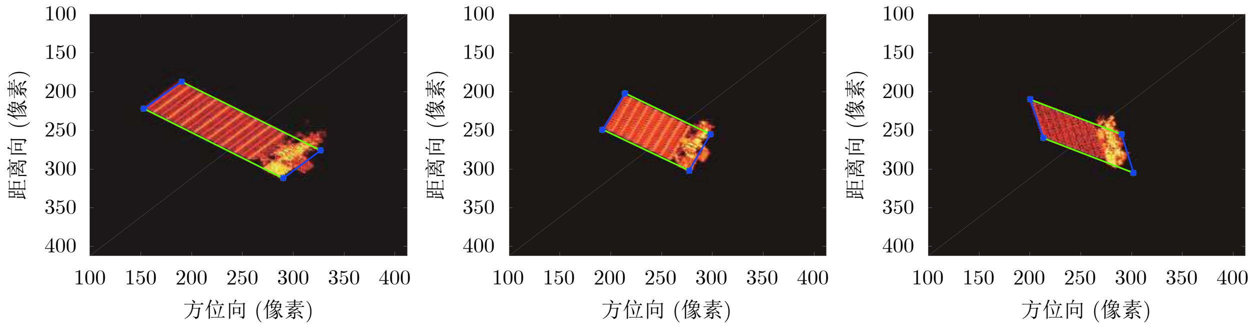
ISAR成像几何标定困难问题，实现失稳目标在轨状态信息的精细化估计。如图19所示，多站地基ISAR同步观测方式利用雷达图像特有的多普勒维度信息与目标雷达间相对运动的直接联系，分步实现目标瞬时姿态与自旋运动的参数估计，验证了雷达传感器在空间自旋目标状态感知应用上的“天然优势”[54]。雷达-光学异视指在相同视角观测得到光学成像平面和雷达成像平面始终正交。如图20所示，同一观测视角下这两个成像平面在空间中互相垂直，目标在这两类图像内投影信息互补[55]。这种光电联合观测策略在不增加观测站点的情况下有效解决了单站单传感器观测的角度局限性，可以广泛应用于各类多传感信息融合任务。

另外，针对ISAR图像序列相位信息的解译也是该成像结构反演方向的一个重要研究内容。日本三菱电机公司的Suwa等人[56]提出利用多视角ISAR对目标进行序列成像，根据多组图像内散射点特征变化来估计目标的转动参数和散点位置。与InISAR干涉相位解算散射点高程信息不同，该方法将多站观测间的相位差用于估计目标运动。西安电子科技大学的张磊、周叶剑等人[57,58]类比光学图像因景深产生的散焦现象，将ISAR成像散焦现象与目标雷达间相对运动补偿过程联系起来，提出了利用回波二次相位系数解算目标在轨姿态参数，并将其推广至面向非平稳目标的多站联合测量模式。这一方式实现了ISAR图像二次相位的“变废为宝”，为雷达成像、图像解译等相关领域研究提供了一个新的视角与思路。

但无论是基于目标ISAR图像投影形态特征还是相位特征的结构反演技术在实际应用过程中均对地基雷达成像观测孔径流形提出较高要求。尤其是通过图像序列估计目标在轨参数时，观测视角在距离、方位两个维度的变化幅度失配将直接影响最终结果的准确性。因而，该类方法需要面向实际观测场景结合目标轨道运动模型进行进一步优化。

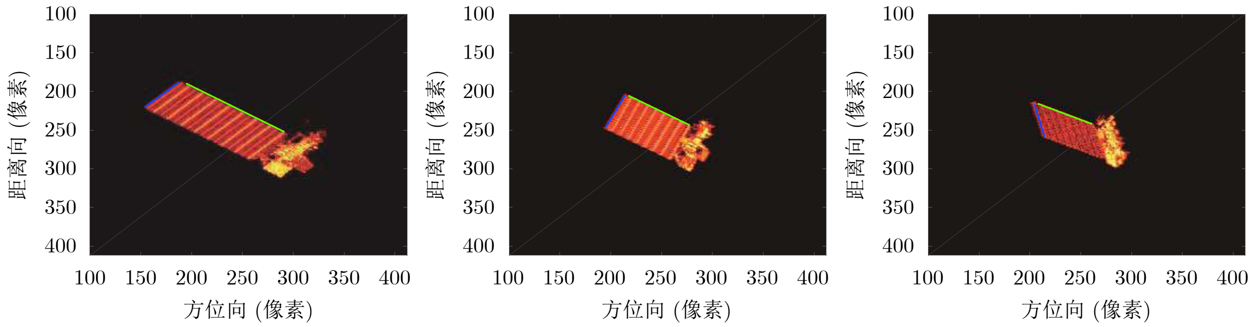
4　目标状态自估计更新技术

“自估计(Ego-motion Estimation)”技术主要



(a) 原始序列

(a) The original observation sequence



(b) 重建序列

(b) The reproduced sequence

图 17 原始观测序列与估计重建图像序列对比[51]

Fig. 17 The comparison between the original observation sequence and the reproduced sequence with estimated attitude parameters[51]

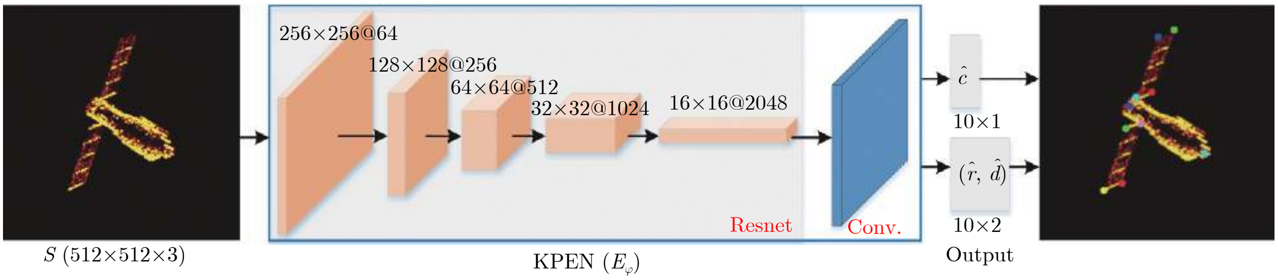


图 18 KPEN关键点提取流程[53]

Fig. 18 Target scattering point extraction using KPEN[53]

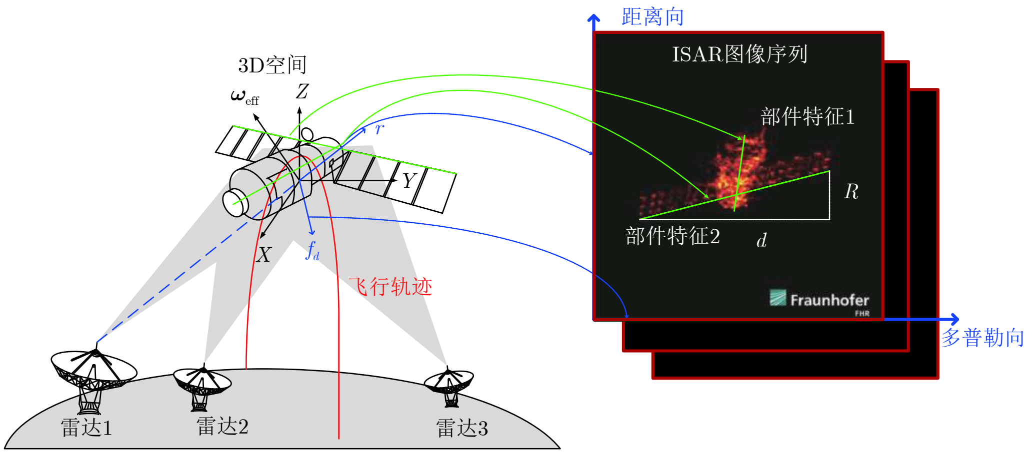


图 19 多站ISAR同步成像瞬时姿态测量[54]

Fig. 19 Target instantaneous attitude estimation via multiple-station ISAR imaging[54]

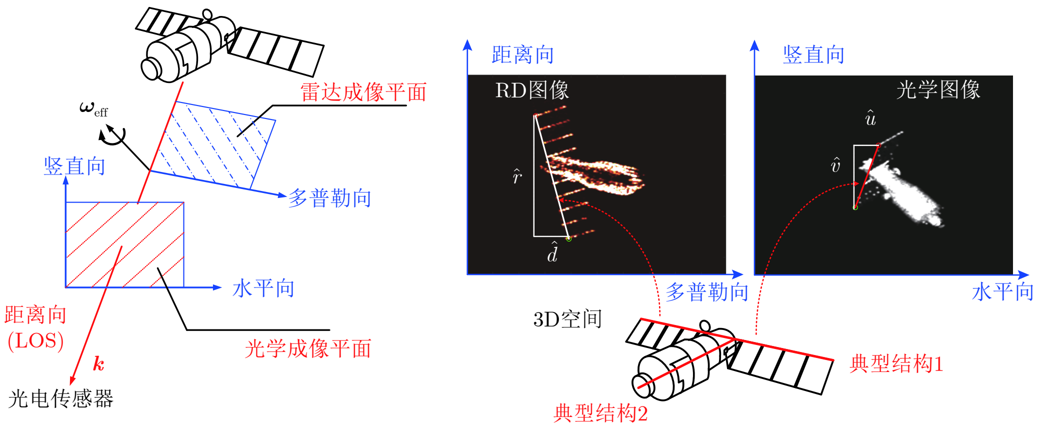


图 20 同视角光电成像瞬时姿态测量[55]

Fig. 20 Target instantaneous attitude estimation via optical-and-radar joint imaging[55]

通过分析目标传递到地面观测站点的自身INS (Inertial Navigation Systems), GPS (Global Positioning System)播报或对地遥感图像等观测数据来判定目标在轨状态。应用传感器测量数据的方法多采用如Kalman滤波等算法对目标进行状态估计、更新与控制。1982年，NASA Goddard航天飞行中心的Lefferts等人[59]较为全面地总结了在配备三轴陀螺仪和姿态传感器条件下的适用于空间目标姿态控制的估计方法。后续该类方法得到持续研究[60–65]，如纽约州立大学的Kim等人[60]根据光学传感器获取的目标视角信息与陀螺仪测量值，结合动力学模型在扩展卡尔曼滤波框架下估计目标相对姿态、位置和陀螺仪偏差。而应用目标观测数据的方法则在研究思路上与同步定位与建图(Simultaneous Localization and Mapping, SLAM)问题相近，通过目标自身观测数据与场景真实空间先验构建目标观测状态评估方案。意大利波伦亚大学的Carozza等人[66]针对空间卫星对地观测场景，提出根据目标传回地表图像与理论模拟图像间的差异对目标在轨姿态进行估计与评估，如图21所示。现阶段，这一类视觉方法研究重心在于图像特征层面的表述与相似度评价[67,68]。总的来看，自估计方法在实际中多适用于存在目标与观测者稳定通信的合作目标态势感知，目标状态估计精度取决于传递信息的准确性，但对于非合作目标或失控、失联目标观测分析精度受限。

5　总结与展望

地基ISAR系统通过窄带精密跟踪、宽带高分辨成像的工作模式，可全天时、全天候地为空间目标状态分析工作提供高质量的观测支持。本文结合地基ISAR雷达设备发展，对空间雷达成像目标在轨状态估计技术进行了归纳总结，介绍了3种现有在轨目标状态信息获取的技术思路，展示了相关具有代表性的研究成果，并对其特点进行简要论述。

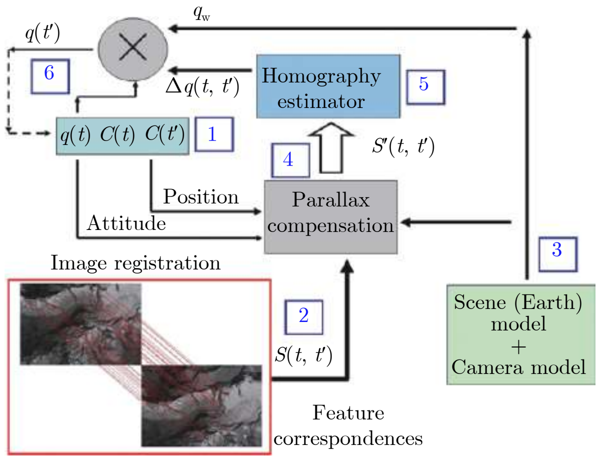


图 21 文献[66]中的目标姿态估计流程

Fig. 21 The flowchart of attitude estimation method in Ref. [66]

(1) 数据特征匹配技术主要依赖现有观测数据积累，多适用于已知目标观测场景；

(2) 三维成像重建测姿技术立足于ISAR成像几何模型，可用于非合作目标监测，但对ISAR图像特征处理要求较高；

(3) 状态自估计技术则采用了目标与观测者间数据通信的主动式状态更新，仅限于合作目标监测。

近年来，随着各国航天活动日趋频繁，复杂空间环境下合作、非合作空间目标实时状态监测需求愈发凸显。如何快速地处理地基观测成像处理数据，获取精细化的目标在轨状态信息仍是一大挑战。从现阶段目标在轨状态估计的研究基础来看，以下方面仍需展开深入研究：

(1) 多源传感器成像信息融合：对于空间目标观测场景，传感器成像几何流形是感知目标状态的核心资源。多站联合成像的方式通过直接增加观测

角度资源，实现了观测资源调度的“以‘空间’换取‘时间’”；而光学-雷达成像融合的方式则是突破了单类传感器观测视角的局限性，实现同视角下光学-雷达感知互补。这两条技术思路有望成为未来空间态势感知网络体系建设的核心内容，相关的理论知识以及工程设备将会是学术界以及各国工业部门在空间态势感知领域的发展重心，有深入研究的价值。

(2) 目标成像信息智能化解译：现阶段空间目标状态估计过程中，对于ISAR图像特征的提取大多依赖人工参与，对目标结构先验需求偏高，在处理大数据量、多种类目标的连续观测任务中面临挑战。另外，随着深度学习等机器学习技术在雷达成像增强、目标识别等方面研究的日趋成熟，深度利用机器学习技术解决目标成像特征自动提取、准确关联识别问题有望成为目标成像信息智能解译的一条潜在途径。从现阶段研究基础来看，该方向的未来研究需要围绕着仿真图像训练结果如何迁移至实测数据处理应用这一技术难点进行探究。

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Review of On-orbit State Estimation of Space Targets with Radar Imagery

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Abstract: Space target state estimation aims to obtain target's on-orbit attitude, structure, movement, and other parameters accurately. This process helps observers analyze the target action intention, check for potential fault threats, and predict the development of on-orbit situations. It is also the core technique in the field of space situation awareness. At present, the estimation of the on-orbit state of space targets primarily relies on external observations from high-performance sensors, such as radars, paralleled by the emergence of a series of representative methods. This paper briefly introduces the development status of Inverse Synthetic Aperture Radar used for space target monitoring at home and abroad. Then, several representative methods, including data feature matching, three-dimensional (3D) imaging reconstruction, and multi-look fusion estimation, are introduced. The data feature-matching technique performs well given a priori target 3D model and scene conditions. The state estimation with 3D geometric reconstruction could precisely describe the target, but high-level observation conditions are required. Finally, the future development trend in this direction is forecasted.

Key words: Space situation awareness; Inverse Synthetic Aperture Radar imaging; Multi-sensor data fusion; Target state estimation

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1 Introduction

With the development of the space technique, space resources are rapidly constructed by countries worldwide. Equipped with high-resolution sensors, considerable space targets have been sent into orbits, which provides information for military reconnaissance, real-time communication, resource exploration, and other space activities. By April 2021, more than 36,000 artificial targets have been launched, and over 22,000 targets are still operating in orbit[1]. As commercial space activities are frequently held, such as SpaceX's Starlink program, the number of on-orbit targets will continuously increase. Consequently, the space orbit resource will be further compressed, and the risk of interaction between targets will increase. The first satellite collision happened between Iridium-33 and Universe-2251 in February 2009, which generated considerable debris threatening the security of nearby targets[2,3]. Therefore, on-orbit state estimation of space targets becomes necessary in Space Situation Awareness (SSA) applications.

In general, high-resolution imaging sensors are used in state analysis of on-orbit space targets. For a long time, many aerospace powers have been actively developing high-performance observation equipment such as optical and infrared sensors[4–16]. Among them, the ground-based Inverse Synthetic Aperture Radar (ISAR) has attracted considerable attention because of its high-

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resolution and all-weather detection capability. In 1970, using ARPA Lincoln Laboratory C-band Observables Radar (ALCOR), MIT Lincoln Laboratory achieved high-resolution imaging and state monitoring for near-earth targets, such as the Salyut-1 space station and Skylab space station[8,9]. These achievements have greatly promoted the development of space target monitoring techniques[10,11]. Another typical ISAR equipment is the MIT Haystack radar. In the past decades, it has been upgraded many times. At present, its band reaches W-band (96 GHz), and the bandwidth has been expanded to 8 GHz. In addition, the observation range is more than 40,000 km. Combined with the HAX radar and other nearby broadband radars, it forms the Lincoln Space Surveillance Combined Network for missile defense and SSA applications[12]. Moreover, the tracking and imaging radar (TIRA) is an important approach for the European Space Agency (ESA) to observe Low Earth Orbit (LEO) satellites. It can achieve 360° orientation and 90° pitch full-angle scanning. The spare time for one 360° circular scanning is only 15 s. As shown in Fig. 1, it supports the high-resolution imaging for targets in a range of space observation activities[13–15]. Furthermore, the French space surveillance radar GRAVES and the French Voronezh radar are the major ground-based radar equipment for space target situational awareness missions worldwide. Chinese space observation ISAR equipment is also developing rapidly. In 1993, the first ground-based ISAR system was produced. At present, a space observation radar system has been built in the initial stage, which is used for the identification and monitoring of space targets. In April 2018, it supported the monitoring of the re-entry of Tiangong-I[16].

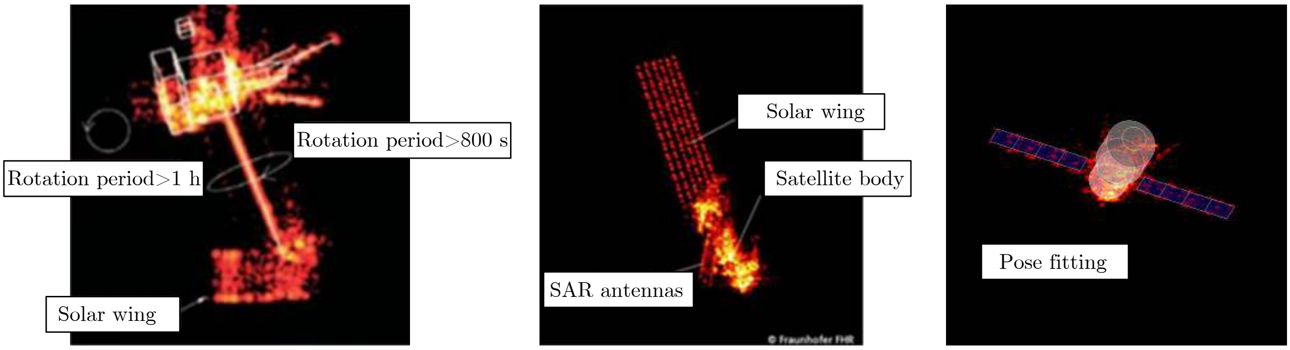
Reviewing the development of the target state monitoring technique, the research focus of ISAR imaging detection has gradually shifted from high-resolution imaging to imaging information interpretation. It can accurately obtain key information from ISAR images, such as target shape, size, and scattering mechanism. This information directly provides the technical support for SSA, satellite state adjustment, and complex space activities. In this paper, existing technical methods are sorted into three classes: data feature matching, three-dimensional (3D) imaging reconstruction, and target ego-motion estimation. Finally, the future development trend in this direction is also forecasted.

2 Data Feature Matching

Data feature matching between the observed sample and a historical dataset is a classical approach to estimating target state parameters through external sensing devices. Normally, the related works are based on the one-dimensional (1D) relative position of the laser reflecting unit or Radar Cross Section (RCS) sequence measurement and two-dimensional (2D) radar image morphological analysis. The dataset is built by computer simulations or long-term accumulation of actual measured data. This method has been applied in many important space activities.

2.1 One-dimensional relative position feature matching

For the space target equipped with a Corner-



(a) ISAR imaging result of Adeos (b) ISAR imaging result of Envisat (c) ISAR imaging result of TG-I

Fig. 1 ISAR imaging result of three space targets by the TIRA system[13–15]

Cube Reflector (CCR), a typical estimation method is matching the relative position measurement by using a laser sensor[17–20]. From 2013 to 2015, the International Laser Ranging Service (ILRS) organized global laser observatory sites to track Envisat, an environmental resource satellite that lost connection with the ground. It carries a Retroreflector Array (RRA) consisting of nine CCRs (Fig. 2). Based on the relative position changes of RRA, Kucharski *et al.*[17] of the Austrian Institute of Technology obtained the attitude and motion parameters of the satellite and then performed a fitting and statistical analysis of its long-time state (Fig. 3 and Fig. 4). This method is demonstrated in their previous study on the on-orbit spin analysis of Ajisai[18] and further applied in other subsequent studies on the influence of gravity gradients on the motion of Envisat[19,20].

Similar to the 1D CCR relative position measurement, target RCS sequence features can be used for parameter estimation of the on-orbit satellite. Zhong *et al.*[21] of Xi’an Satellite Measurement Center proposed to match the actually measured RCS sequence with the RCS simulation sequence generated from the electromagnetic simulation and then use a Hybrid Particle Swarm Optimization (HPSO) algorithm to achieve the optimal solution of target on-orbit parameters. The schematic diagram of ground-based RCS measurement is shown in Fig. 5. The actual measurement and simulation results of the target RCS sequence are compared, and the results are shown in Fig. 6. Lu *et al.*[22] further investigated the attitude estimation for the target spin case.

2.2 Two-dimensional radar imaging feature matching

MIT Lincoln Laboratory started the research on utilizing space target radar images to extract geometric topological features. Consequently, target modeling, data accumulation building, and target classification recognition are achieved for SSA applications using the semantic network. D’Amico *et al.*[23] of Stanford University proposed that the target state can be determined by comparing visual features between the target 3D model and its spaceborne image (Fig. 7). In their subsequent work, the target contour and boundary information are extracted from simulated ISAR images and then used to build a target classification model using similarity judgment[24,25].

Lemmens *et al.*[26] of ESA combined the TIRA radar system features to establish a simulated image database for cooperative targets. They proposed that the on-orbit attitude parameters of targets can be determined by matching the measured ISAR image target boundary information in the simulated dataset. In addition, an engineered software system is designed (Fig. 8), which is applied to monitor the actual state of on-orbit satellites such as Envisat. In their subsequent study, the factors that may affect the matching accuracy are also discussed[27]. Avilés *et al.*[28] of GMV

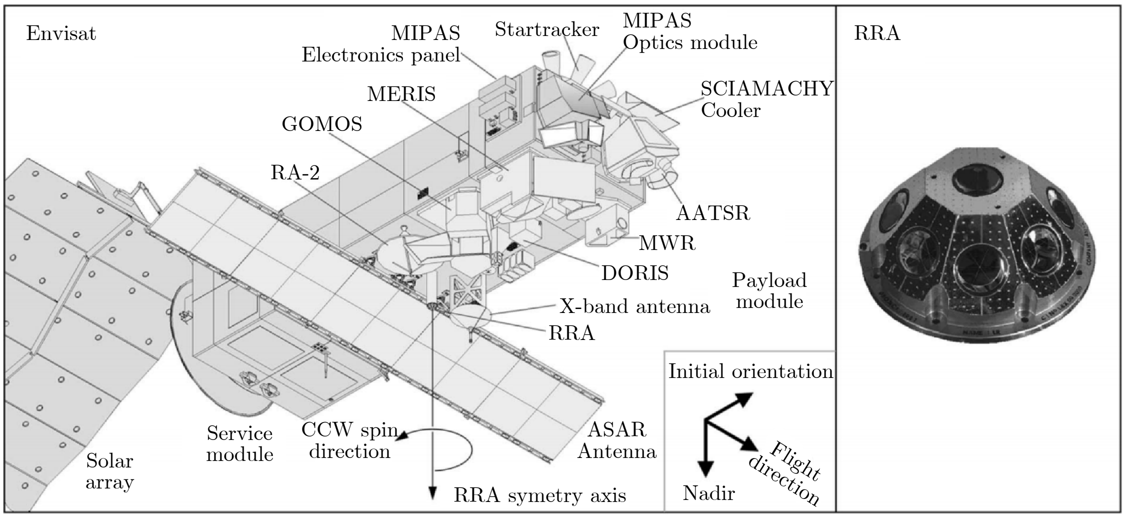
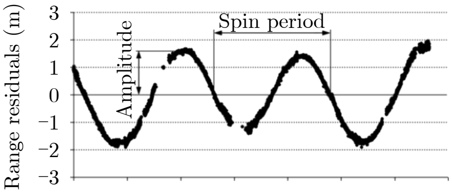
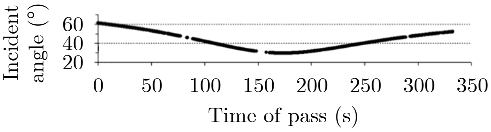


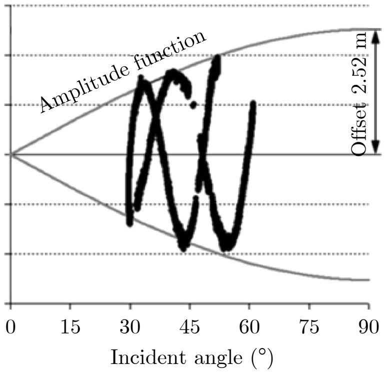
Fig. 2 Envisat and its RRA courtesy of ESA



(a) Distribution of range residuals



(b) Incident angle between the laser vector and the symmetry axis of the retroreflector panel



(c) Representation of the amplitude function (A=2.52 sin(incidentangle))

Fig. 3 Range residuals calculated for Envisat pass measured by Graz SLR station on July 12, 2013[17]

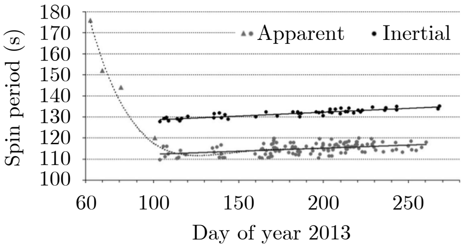


Fig. 4 Spin period analysis of Envisat in 2013[17] (black points indicate an inertial spin period and gray points apparent spin period)

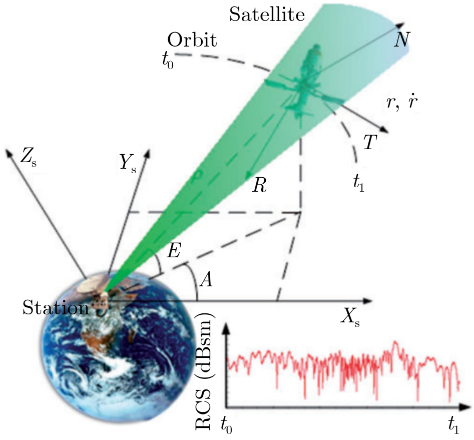
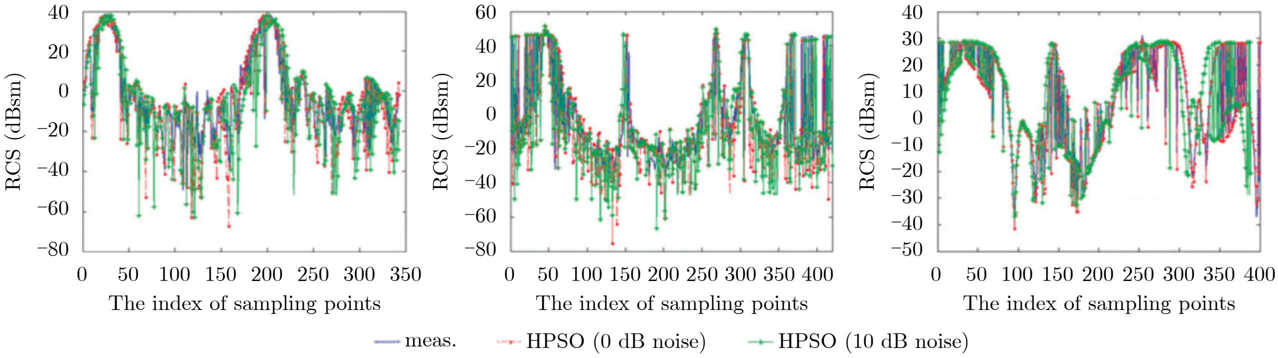


Fig. 5 RCS measuring geometry configuration of space targets via ground-based radar



(a) The RCS sequences of station 1 (b) The RCS sequences of station 2 (c) The RCS sequences of station 3

Fig. 6 Comparison between measured RCS sequences and the RCS sequences[21]

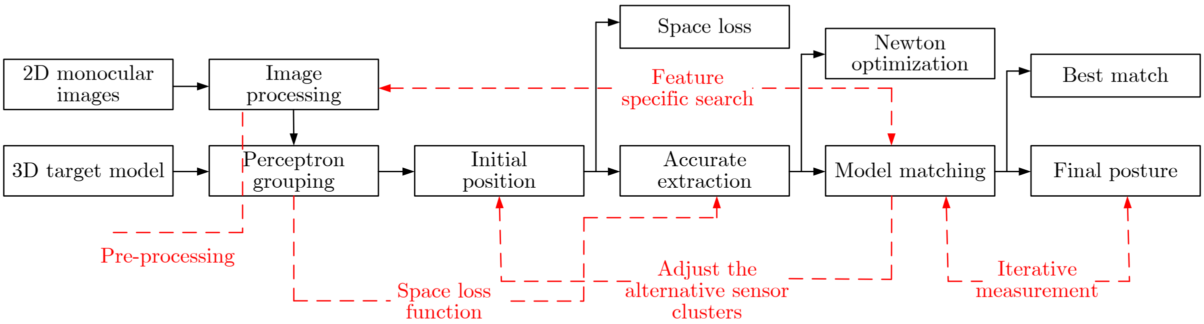
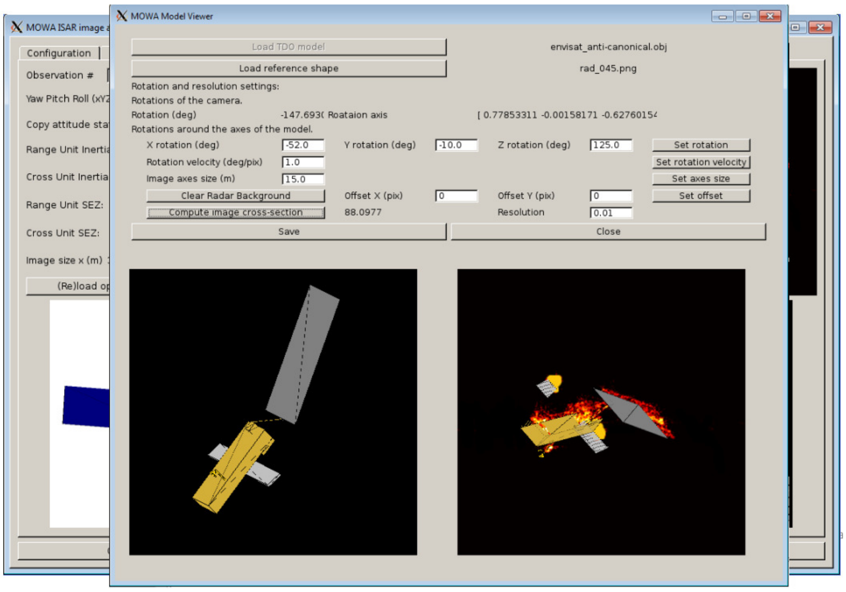


Fig. 7 The flowchart of attitude estimation method in Ref. [23]



envisat_anti-canonical.obj

rad_045.png

Rotation and resolution settings:

Rotations of the camera.

Rotation (deg) -147.693(Roataion axis [0.77853311 -0.00158171 -0.6276015‹

Rotations around the axes of the model.

X rotation (deg) -52.0 Y rotation (deg) -10.0 Z rotation (deg) 125.0

Rotation velocity (deg/pix) 1.0

Image axes size (m) 15.0

Offset X (pix) 0 Offset Y (pix) 0

88.0977 Resolution 0.01

Fig. 8 Graphical interface of MOWA target attitude fitting[27]

Aerospace achieved automatic state measurement (Fig. 9). Furthermore, Yang *et al.*[29] of Fujian Agriculture and Forestry University considered the structural constraint between the main axis direction of the target body and the solar wing and achieved target pose estimation by matching sequential image changes.

In general, target state parameters can be determined by data matching when the accumulated sample is sufficient. This method is suitable for the state estimation of collaborative satellites as their long-term observation can be easily collected. However, it does not work when the target model is unknown, or the accumulated observation data are limited.

3 Three-dimensional Imaging Reconstruction

3D imaging reconstruction aims to build a geometrical model of ground-based ISAR imaging. In particular, it aims to achieve target on-orbit state estimation by the direct or indirect math expression between the target image feature and its 3D construction. Based on the optical image interpretation in the computer vision field, related research on radar image interpretation also provides new perspectives on microwave vision[30,31].

3.1 Target scattering points reconstruction using history matrix decomposition

Target 3D information can be obtained from ISAR images sequenced by the Matrix Singular Value Decompose (SVD), namely, the Factorization Algorithm (FA). In general, this class of algorithms is based on the classical structure of motion methods in computer vision[32,33]. The SVD algorithm is adopted to decompose the target scattering point observation matrix (*e.g.*, Range-Doppler matrix) extracted from ISAR images. Consequently, the target structure matrix and measurement matrix are solved to provide the shape and position information of the satellite in 3D. In 1992, based on the perspective imaging mechanism of an optical camera, Tomasi *et al.*[34] of Cornell University proposed that target 3D structural information can be recovered from the relationship between the image stream feature of a rigid target and its motion model. In 2009, M. Ferrara *et al.*[35] of the U.S. Air Force Research Laboratory refined this method for radar image processing. Target scattering points are recovered from the target 1D radar distance matrix (Fig. 10). Later, they introduced a priori structural information to improve the robustness of this method in their subsequent study[36].

In addition, McFadden[37] of General Dynamics Advanced Information Systems extended the FA to a 2D radar imaging scene. In particular, the target 2D coordinates in the ISAR image sequence are used to calculate its 3D structure. Then, a case of an actual ship is provided (Fig. 11).

Fig. 9 Attitude estimation for Envisat sequence frames after constraining the search space[28]

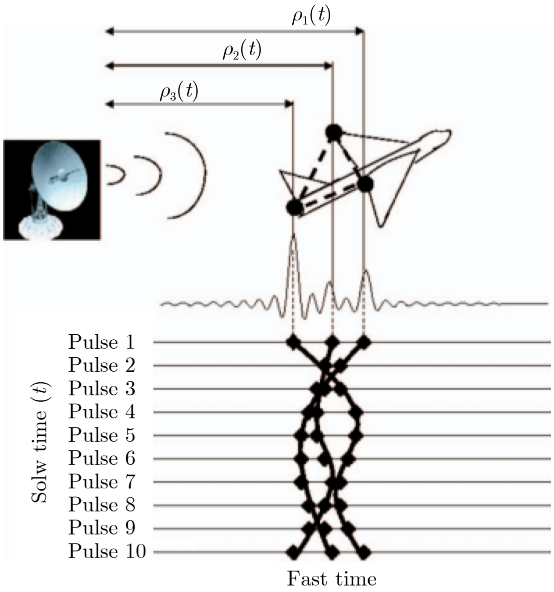
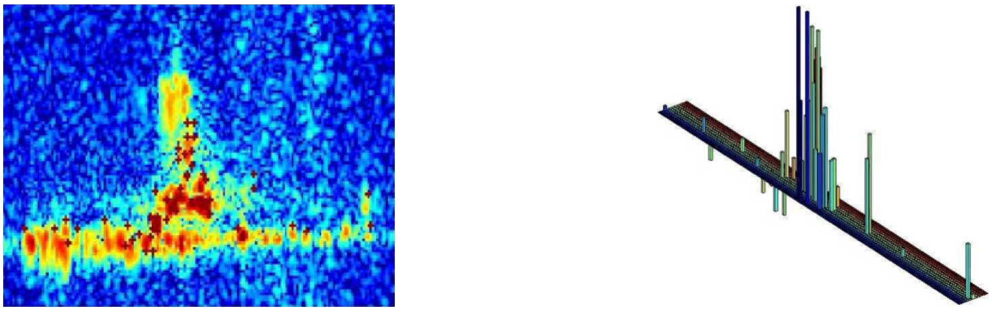


Fig. 10 Recording the distance sequence of target scattering points through radar ranging[35]

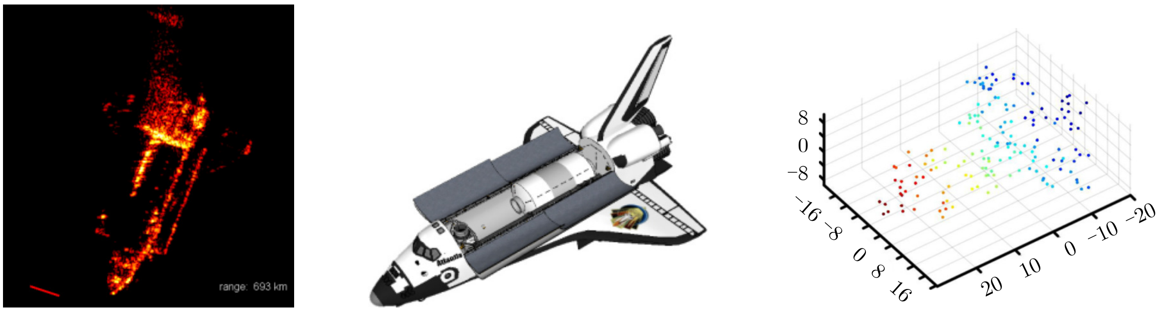
Moreover, Wang *et al.*[38,39] of Fudan University applied this method to sparse the imaging scene. The compression perception algorithm is used during the decomposition of the scattering point sequence. A case of multi-angle shuttle ISAR images is shown in Fig. 12.

Notably, the optical camera calibration method cannot directly solve the target ISAR measurement matrix calibration because of the difference between radar and optical imaging mechanisms. At the current stage, rotation matrix calibration is required. In addition, this method is based on the premise of the accurate association of target key points between multi-view images. Nevertheless, achieving robust association when scattering characteristics fluctuate in the long-term ISAR



(a) The extraction of the scattering points in the measured ISAR image (b) The 3D reconstruction result of the ship

Fig. 11 Scattering point reconstruction result of the ship[37]



(a) Measured ISAR sequence (b) 3D model of the shuttle (c) 3D reconstruction result of the shuttle

Fig. 12 Reconstruction result of shuttle in sparse observation[38]

observation sequence, that is, the Angular Glint problem, remains a challenge[40,41].

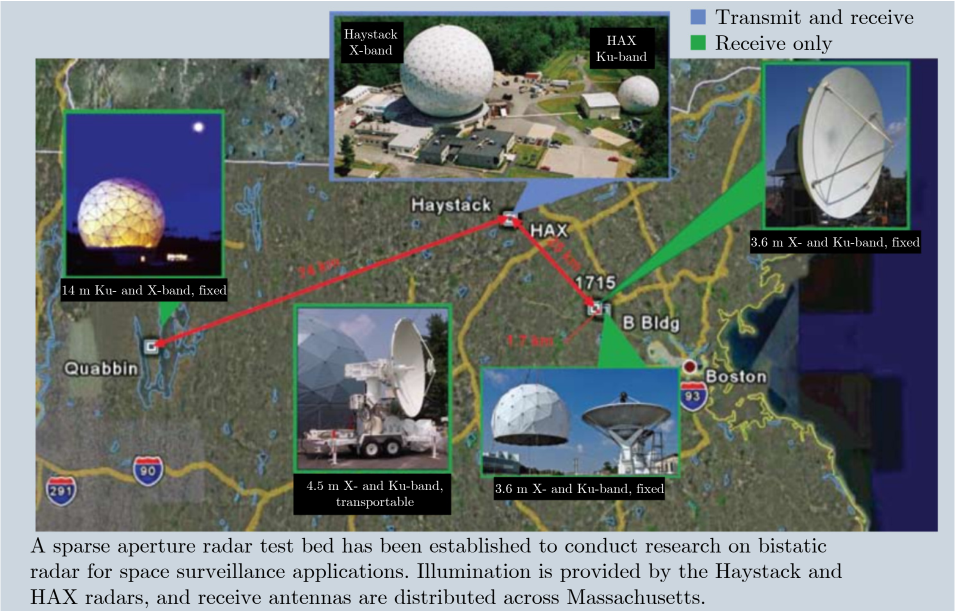
3.2 Interference three-dimensional imaging of multi-channel inverse synthetic aperture radar

The interferometric synthetic aperture 3D imaging technique is widely used in the direction of remote sensing applications[42–44]. The 3D information of each scattering point is recovered in accordance with the phase difference of multi-channel or multi-pass radar images after image registration. With the development of ground-based ISAR equipment, interferometric measurement is also used in the identification of ship and space targets. As shown in Fig. 13, the U.S. Lincoln Laboratory builds a space surveillance network system consisting of Haystack, HAX radar, and other distributed receivers to perform Interferometric ISAR (InISAR) measurements for LEO space targets[45,46]. The experimental results are shown in Fig. 14.

Zhao *et al.*[47] of the Beijing University of Technology discussed the configuration of cross-shaped and L-shaped antennas for the InISAR system and analyzed the effects of horizontal and vertical baseline lengths on the estimation accuracy of the target 3D structure in detail. They also proposed a 3D interferometric imaging method for different observation arcs of space targets[48]. In addition, Shao *et al.*[49] of Xidian University extended the multi-channel InISAR imaging method in sparse observation, where the joint high-order phase compensation of multi-channel echo is made using a compressed sensing technique. Its performance is validated using real Yake-42 aircraft data (Fig. 15). In on-orbit satellite observations, the InISAR 3D imaging results are directly provided using the 3D point cloud. It can be applied to obtain target state parameters, such as the target attitude vector. However, obtaining target high-precision dense point cloud remains a challenge because of the baseline length limitation of the ground-based InISAR equipment. Moreover, the interference phase processing for artificial targets must be further investigated.

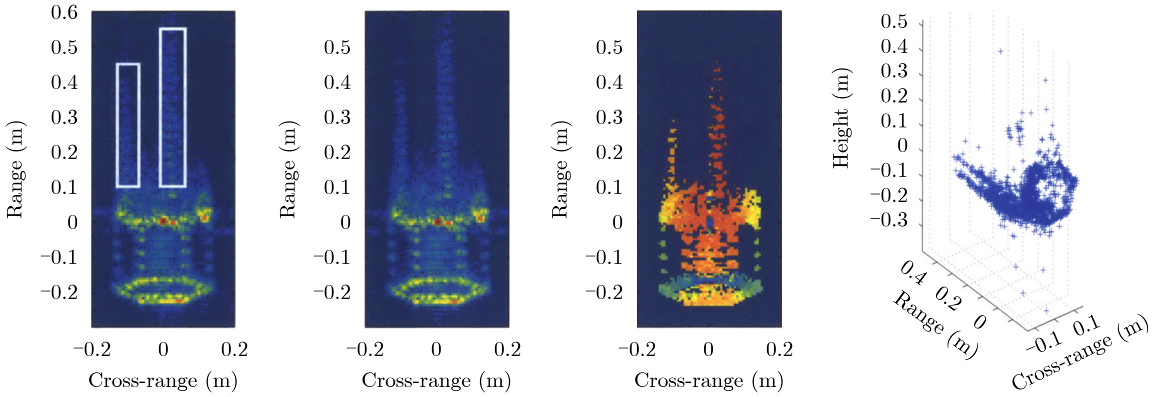
3.3 Target structure inversion under a radar projection imaging model

Establishing a mathematical expression between the target state and its ISAR image fea-



A sparse aperture radar test bed has been established to conduct research on bistatic radar for space surveillance applications. Illumination is provided by the Haystack and HAX radars, and receive antennas are distributed across Massachusetts.

Fig. 13 InISAR measuring system for space targets in MIT Lab[45]



(a) Channel 1 (b) Channel 2 (c) Phase difference map (d) Reconstruction results

Fig. 14 InISAR processing of SPASE satellite[46]

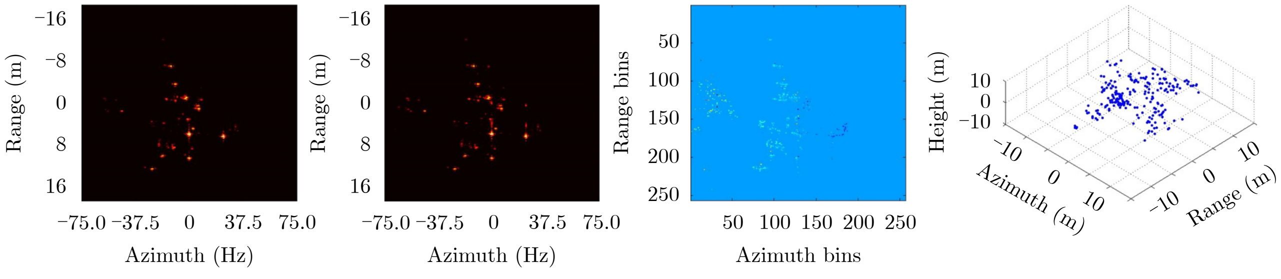
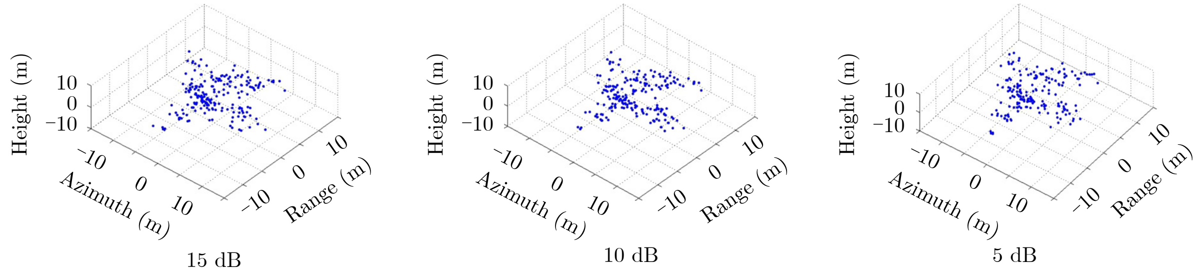


Figure 1 Figure 2 Interference phase 3D interference ISAR map

(a) 3D interferometric ISAR imaging results of real aircraft targets



(b) 3D imaging effect with different signal-to-noise ratio

Fig. 15 InISAR 3D imaging result of Yake-42[49] tures is another important approach to obtaining target on-orbit state parameters. In 2001, Mayhan *et al.*[50] of MIT Lincoln Laboratory proposed that the target ISAR imaging can be considered as a projection transformation of the target 3D scattering points on the 2D radar imaging plane. With Geometrical Theory of Diffraction (GTD), projection matrix $\boldsymbol{A}$ is used to describe this process in the target Cartesian coordinate system (Fig. 16). On this basis, Zhang and Zhou *et al.*[51] of Xidian University derived an explicit expression of on-orbit attitude parameters with its rectangular component projection changes in an ISAR image sequence. Using the estimated attitude parameters, the 3D model is rotated to this pose, and a simulated observed image sequence can be reconstructed in the same observation view. Therefore, the reliability of the estimation result can be qualitatively verified by visual comparison using the original image sequence (Fig. 17).

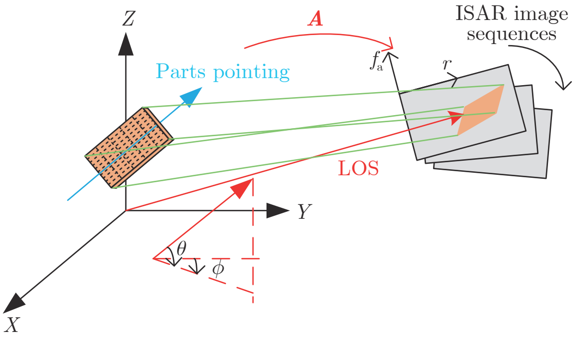
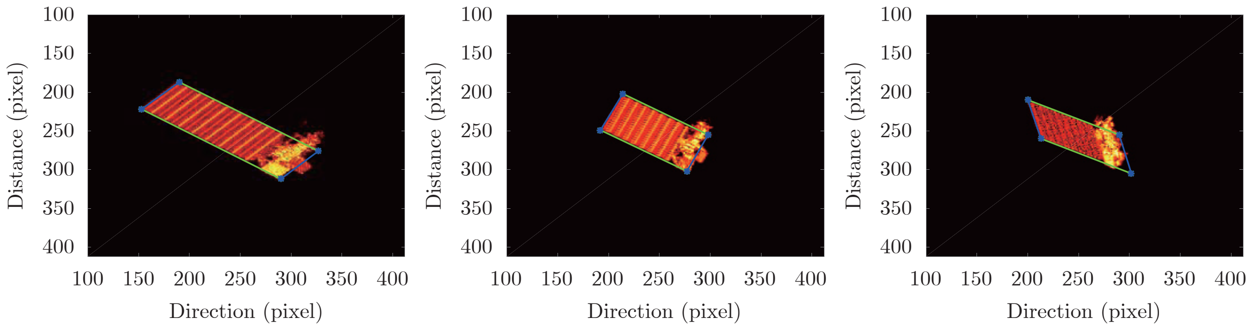


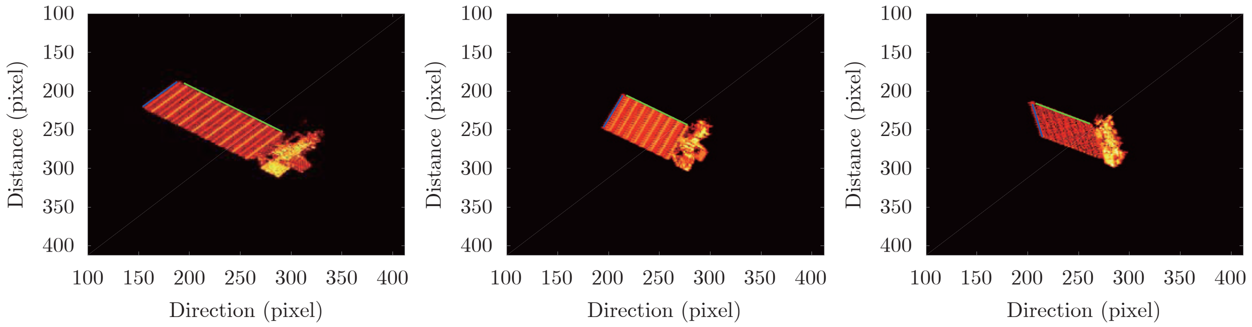
Fig. 16 Geometrical model of ISAR projection imaging

Afterward, Wang *et al.*[52] of the National University of Defense Technique further proposed to use different projection characteristics of target line structures in the image sequence. In addition, Xie *et al.*[53] of Sun Yat-sen University used machine learning to achieve the automated estimation of the target pose. In particular, a Key Point Extraction Network (KPEN) is built to extract key points of the target structure from ISAR image sequences. An example based on simulated TG-I images is shown in Fig. 18.

Zhang and Zhou *et al.*[54,55] of Xidian University introduced multi-station joint and optical–radar fusion strategies in their subsequent research to address the target dynamic estimation of spin satellites. It overcomes the difficulty of geometric calibration of radar imaging caused by target spin motion. As shown in Fig. 19, the Doppler dimension information of radar images is connected with the relative motion and



(a) The original observation sequence



(b) The reproduced sequence

Fig. 17 Comparison between the original observation sequence and the reproduced sequence with estimated attitude parameters[51] used to estimate the target instantaneous attitude and spin parameters[54]. For the optical-radar fusion strategy, the imaging planes of these two sensors are perpendicular at the same view angle. That is, target projection information in radar and optical images is complementary[55](Fig. 20). This observation strategy solves the angular limitation of single sensor observation without increasing the number of observation stations, which can be used in multi-sensor fusion tasks.

On the contrary, interpreting phase information of ISAR image sequences is important for target structural analysis. Suwa *et al.*[56] of Mitsubishi Electric Corporation proposed to estimate target rotation parameters and position in accordance with its scattering feature in a multi-view ISAR image sequence. Apart from interpreting the interferometric phase during InISAR processing, it uses the phase difference between different view observations to estimate the target motion. Zhang and Zhou *et al.*[57,58] of Xidian University proposed the use of quadratic phase coeffi-

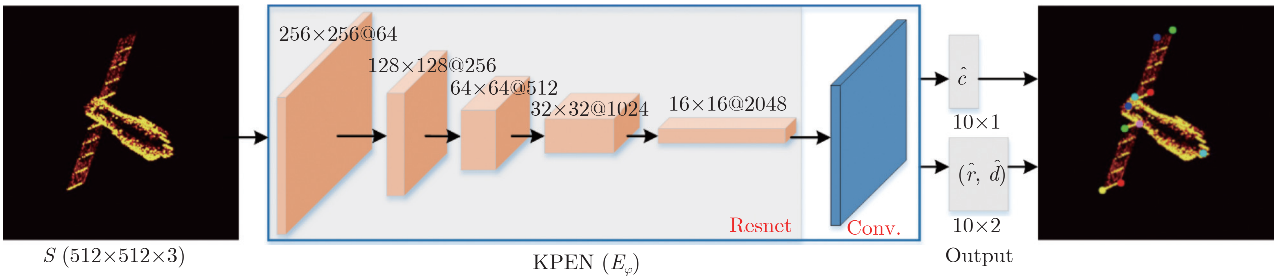


Fig. 18 Target scattering point extraction using KPEN[53]

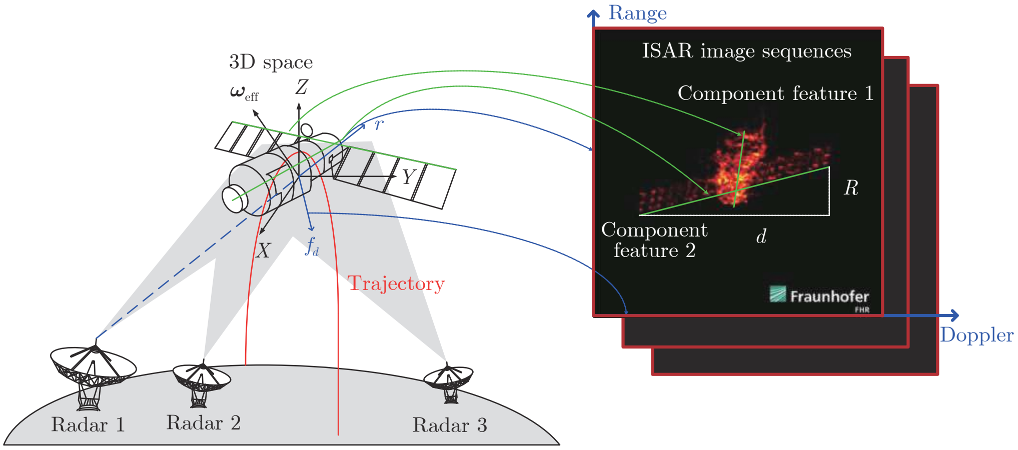


Fig. 19 Target instantaneous attitude estimation via multiple-station ISAR imaging[54]

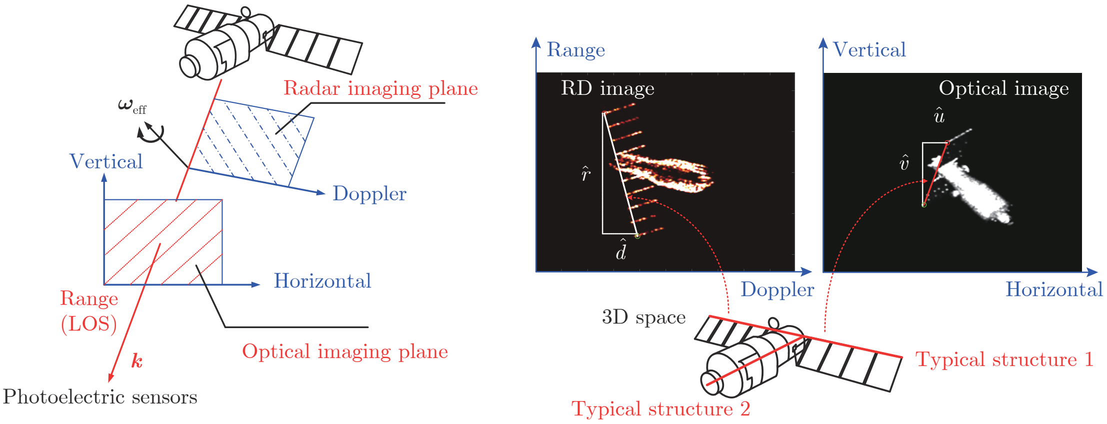


Fig. 20 Target instantaneous attitude estimation via optical-radar joint imaging[55]

cients of a single ISAR image to achieve the target attitude estimation. Based on the image depth analysis of the optical image, the defocus information in ISAR images is considered with radar LOS relative motion. It is also extended to multi-station cases for the dynamic estimation of spin targets. Moreover, it provides a new perspective on ISAR image application. Quadratic phase terms, which are usually compensated for the sake of improving the focal performance of ISAR imagery, are directly used in target motion estimation.

4 Target Ego-motion Estimation

Target transmission data received on the ground, such as Inertial Navigation Systems (INS) parameters and Global Positioning System (GPS) broadcast produced remote sensing images, which can be used for target ego-motion estimation. Some filtering algorithms, such as Kalman filtering, are applied to update and predict the target motion state for attitude control. In 1982, Lefferts *et al.*[59] of NASA Goddard Space Flight Center summarized the studies on satellites equipped with three-axis gyroscopes and attitude sensors. Afterward, this method has received considerable attention [60–65]. Kim *et al.*[60] of the State University of New York proposed that the target relative attitude, position, and gyroscope deviation can be estimated in an extended Kalman filter framework based on target view information and gyroscope measurements.

The estimation method of applying target observation data is similar to the solution of the Simultaneous Localization and Mapping (SLAM) problem. A target state assessment scheme can be constructed in accordance with the target observation data and prior scene information. Carozza *et al.*[66] of the University of Bologna proposed that the target attitude can be evaluated by the difference between the surface image returned by the satellite and the theoretical simulation (Fig. 21). At this stage, this type of visual method focuses on the representation and similarity evaluation of the image feature[67,68].

In general, target ego-motion estimation is suitable for the tasks for cooperative situational applications where stable communication between the target and observer exists. The accuracy of target state estimation depends on the accuracy of the transmitted information. However, it cannot be used for non-cooperative targets or disconnected targets.

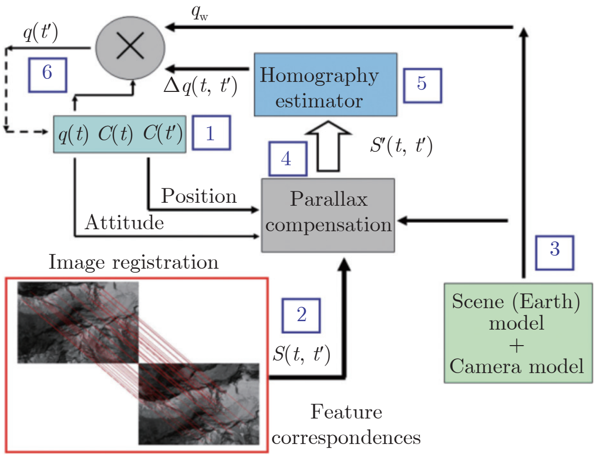


Fig. 21 Flowchart of the attitude estimation method in Ref. [66]

5 Conclusion

The ground-based ISAR system supports the high-quality observation of space targets through its narrow-band tracking and wide-band imaging modes. With the development of ISAR equipment, the on-orbit state estimation of space targets has become a hot topic in the SSA field. In this paper, the related works are sorted into three classes, and their characteristics can be briefly summarized as follows.

(1) Data feature-matching techniques rely on the accumulation of existing observation data, which are available for most known targets.

(2) As it is based on the ISAR imaging geometry model, the 3D imaging reconstruction technique can be used for non-cooperative target monitoring. However, it requires accurate extraction in the ISAR imagery.

(3) Target ego-motion estimation technique uses active state updates with data communication between the target and observer; thus, it only works in the cases of cooperative targets.

Considering the increasing frequency of human space activities, achieving real-time state monitoring of space targets in complex space environments is necessary. At current, obtaining target state information from ISAR images remains a challenge. Thus, we hypothesize the following aspects, which need to be further investigated:

(1) How to achieve data fusion of multi-source sensors for target state estimation? Based on existing works, multi-station joint and optical-radar fusion are two available approaches. Therefore, related theoretical research might be the core of future work.

(2) How to achieve the intelligent interpretation of target imaging information? In the current stage, most works are based on the manual extraction of ISAR image features. When the mass data need to be handled, such as monitoring a satellite constellation, automatic processing becomes increasingly important in the task. The machine learning technique is used in several existing works, which may be another hot topic in the image interpretation of space targets.

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