光学学报

主被动星载大气探测载荷性能对比与分析

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摘要 卫星遥感能够获取全球范围的大气环境参数，主要包括主动和被动两类探测技术。星载激光雷达作为典型的主动光学遥感载荷可以用于探测全球大气气溶胶、云、大气风场和温室气体等，并可以反演垂直廓线信息。本文概述了星载激光雷达探测技术的发展历程，较为全面地总结了星载激光雷达载荷轨道及技术参数，并与被动光学遥感载荷进行了比较，探讨了主被动星载大气探测载荷各自的优劣势和未来发展趋势。通过对比分析，为未来不同应用场景的大气探测载荷选择提供参考，有助于更好地利用卫星数据反演全球大气参数。

关键词 星载激光雷达；主被动遥感；光学载荷；大气环境参数；大气探测

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1 引言

大气环境参数直接影响地球的生态环境和气候变化，从而影响人类的生命健康[1]，例如气溶胶、云和温室气体等通过对太阳光发生吸收和散射作用影响太阳和地球之间的辐射平衡，是造成大气环境污染和极端天气频发的重要原因[2]。同时大气层作为航空航天作业区域，大气温度、压强、密度和大气风场等环境参数对装备的设计和性能指标的实现有着举足轻重的影响[3]。故全球大气环境参数探测一直以来备受各国学者关注。

卫星遥感是一种获取全球大气环境参数的重要技术手段，可分为主动和被动探测两大类别。主动探测又称为有源探测，自身带有辐射源，向目标物发射不同形式的电磁波，不依赖于太阳光，可昼夜工作，常见的主动遥感有激光雷达[4-5]、合成孔径雷达[6]、微波散射计[7]等。被动探测即无源探测，自身无辐射源，需要借助目标物的反射或自然辐射源（如太阳）的电磁波，基于该探测技术的遥感仪器有中分辨率成像光谱仪[8]、测风干涉仪[9]、云与气溶胶偏振成像仪等[10]。相对于主动星载探测技术而言，被动探测载荷发展历史悠久，技术更加成熟，遥感仪器种类和探测目标多样，但存在如依赖于太阳光、探测时间及区域具有局限性等问题。以激光雷达为代表的主动星载探测技术弥补了这些缺点，主被动星载遥感大气探测技术协同发展，为全球大气环境参数探测提供了有力的技术支撑。

目前卫星遥感大气环境探测在云、气溶胶、大气风场、温室气体、温度、压强和密度等参数的探测上作出了巨大贡献，有效解决了大气污染、气候变化等问题。本文介绍了星载激光雷达的发展历程，重点对比分析了主被动星载遥感载荷对主要的大气环境参数进行探测的优缺点，最后总结探讨了主动星载激光雷达和被动遥感大气环境参数探测技术的未来发展趋势。

2 星载激光雷达探测大气环境参数

主动星载高精度探测大气环境参数的载荷主要为激光雷达，自 1960 年第一台激光器的成功研制，激光雷达从诞生到应用已经六十余年，大气探测是激光雷达最先应用、也是最为成熟的领域。按照平台划分，可以将大气探测激光雷达分为地基、空基和天基三种，地基因其探测时间地点方便灵活、人工维护方便和安全性高风险小等优点使得它的探测种类全面且多样，包括米散射激光雷达、偏振激光雷达、拉曼激光雷达、高光谱分辨率激光雷达、多普勒激光雷达、差分吸收激光雷达、共振荧光激光雷达和瑞利散射激光雷达等。激光雷达空基探测主要建立在机载方面，相对于地基激光雷达优势较为明显，解决了人迹罕至地区地基激光雷达无法设立站点的难题，大大增加了探测的范围，常作为星载激光雷达的验证手段。但上面两种探测方式都无法满足全球范围内的连续探测，随着全球环境和

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气候变化等研究的迫切需求，星载激光雷达在地基和机载的研究基础上逐渐发展壮大[11-12]。

1994年9月，美国国家航空航天局（NASA）为了验证星载激光雷达探测的关键技术和发展卫星平台的应用，开展了激光雷达空间技术实验（LITE），一台三波长激光雷达搭载在“发现号”航天飞机上飞行了10天，LITE的设计能够获得云层、平流层和对流层中的气溶胶、大气边界层的高度以及25～40 km高度之间平流层的大气温度和密度。LITE首次获得了全球范围气溶胶垂直廓线数据，利用地基和机载激光雷达对其进行验证，LITE在南大西洋部分地区观测得到的气溶胶散射比与NASA P-3B机载飞行数据一致性较好[13]。Osborn等[14]获取了LITE的532 nm和355 nm高质量平流层气溶胶测量结果，得到了气溶胶垂直结构和光学特性的全球视图，该数据还可用于气溶胶空间分布和传输。Menzies等[15]利用LITE的海面后向散射反演海面风速，表明了星载激光雷达反演大气风场的可行性，LITE虽然工作时间较短，但为星载激光雷达大气探测打下良好的基础，具有里程碑式的意义[16-17]。欧洲航天局（ESA）于1991年正式启动欧洲第一个星载激光雷达计划——大气激光雷达（ATLID）开发计划[18]。该激光雷达的二极管泵浦固体Nd:YAG激光器发射1064 nm波长的激光脉冲，后向散射光被直径为0.6 m的扫描望远镜所接收，期望获得云、对流层气溶胶和大气边界层等大气参数，原计划发射在极地轨道800 km高度，最后因为种种原因没有如期发射[19-21]，但为地球云-气溶胶和辐射探测卫星（EarthCARE）计划提供了宝贵的经验。EarthCARE计划是一项由ESA与日本宇宙航空研究开发机构（JAXA）联合进行的对地观测任务，将主动和被动遥感仪器组装在一起进行探测，卫星搭载四种载荷，分别为ATLID、多光谱成像仪（MSI）、宽带辐射计（BBR）和云剖面雷达（CPR），旨在提供光学薄云和气溶胶的垂直剖面图以及云边界的高度，加强人类对云-气溶胶-辐射相互作用和地球辐射平衡的理解，具有独特的多普勒功能并测量云粒子的垂直速度，另外其运行轨道降至394 km，增加了云探测灵敏度[22-24]。ATLID是一种高光谱分辨率激光雷达（HSRL），基于Fabry-Perot标准具将大气米散射和瑞利散射信号分离，选择紫外光谱范围内的工作波长355 nm，望远镜直径为620 mm。该计划一再推迟，预计2024年发射[24]。

冰、云和陆地高程卫星（ICESat）主要搭载地球科学激光测高系统（GLAS）（图1），是全球首颗对地观测激光测高卫星[25]。ICESat从2003年发射升空至2010年退役，期间提供了冰盖质量均衡、陆地地形、植被、云和气溶胶的分布和垂直结构等数据，为人类了解地球大气和气候变化如何影响极地冰和全球海平面提供了科学依据。GLAS设计有三个激光器，使用波长分别为1064 nm和532 nm的红外和可见光激光脉冲，分别主要对应地表与大气，以40 Hz的频率连续发射，后向散射光被直径为1 m的望远镜接收[26-28]。Hlavka等[29]在美国加利福尼亚州的一次火灾案例中，应用GLAS获取了气溶胶和云的光学厚度，与云物理激光雷达（CPL）一致性较好，Hart等[30]研究发现，GLAS数据能够探测40 km高空大气中气溶胶层分布，ICESat/GLAS被证实其探测云和气溶胶的能力，展示了星载激光雷达在大气科学中的重要作用。作为ICESat的后续任务，美国NASA于2018年9月又发射了ICESat-2卫星，搭载高级地形激光高度计系统（ATLAS），与GLAS不同的是，首次引入的单光子探测技术大大提高了对地探测数据获取频率[31]。ATLAS为单波长激光雷达系统，只有532 nm波长，配备的高重复频率激光器每秒对地发射1万次光脉冲，采用光子计数体制，优化了对地高程测量技术[32]。虽然ICESat-2卫星主要目的是高分辨率测高，但是依然记录从14 km高度到地表的云层和气溶胶的后向散射信息，这为了解气候变化、冰盖消融和海水平面上升之间的相互关系提供了科学依据，但14 km的低高度对于背景计算和校正带来困难，造成白天信号不理想，需要在算法上突破。另外，在云和气溶胶的识别中，由于ATLAS只有一个波长工作，缺乏偏振探测通道，无法识别大气中的非球形粒子[33-34]。

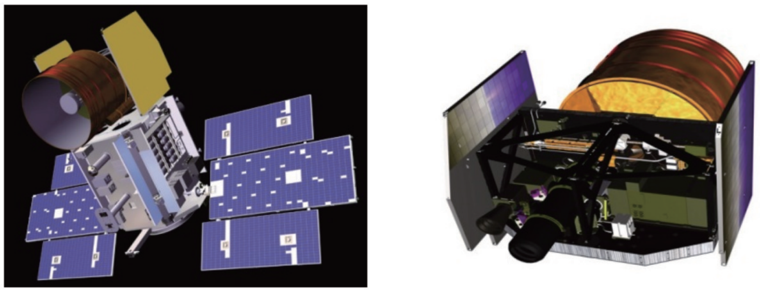

图1　ICESat（左）和GLAS（右）模型图[25]

Fig. 1　ICESat (left) and GLAS (right) models[25]

LITE和ICESat为后面大气探测激光雷达的研制提供了宝贵的经验，但他们搭载的激光雷达并没有测量后向散射信号的偏振信息[35]。美国NASA与法国国家太空研究中心（CNES）合作开发的云-气溶胶激

光雷达和红外探路者卫星观测（CALIPSO）搭载的正交偏振云-气溶胶激光雷达（CALIOP）是一种采用双波长具备偏振探测能力的激光雷达（图 2），另外还有在可见光和红外光谱区域工作的被动成像仪、成像红外辐射计（IIR）和宽视场相机（WFC）[36]。二极管泵浦 Nd：YAG 激光器运用调 Q 和倍频发射 1064 nm 和 532 nm 的线偏振光脉冲，重复频率为 20.2 Hz，能量为 110 mJ，望远镜直径为 1 m[37]。在低对流层，激光雷达空间分辨率表现为垂直方向上 30 m，水平方向 333 m。被动遥感仪器 IIR 幅宽 64 km，提供 8.65、10.60 和 12.05 μm 的辐射测量，优化联合激光雷达探测卷云和粒子尺度，WFC 为改进的星跟踪器相机，幅宽 61 km，覆盖 620～670 nm 波长的光谱区域，为激光雷达测量提供气象背景[38-39]。CALIOP 为星载激光雷达技术取得突破性发展作出了重要贡献，截至目前已经在轨运行了 17 年，远远超过了预期设计，为气溶胶-云-降水的相互作用、全球沙尘分布、传输和污染、天气和气候变化研究等科学问题提供了科学数据[4-5，40]。CloudSat 卫星和 CALIPSO 卫星共同组成 A-Train 卫星星座，CloudSat 卫星是世界首颗专门用于观测全球云层特征的微波主动探测卫星，其上搭载的毫米波云廓线雷达（CPR）额定频率为 94 GHz，采用天底观测方式，CPR 可以探测垂直剖面 125 层，垂直分辨率为 240 m，水平分辨率为 1.4 km×2.5 km，CPR 具有较强的穿透云层的能力。国内学者[41]利用 CloudSat 卫星在 2006—2009 年的数据分析中国及周边地区的云垂直结构特征，并根据气候区域统计分析了云垂直结构分布特征。张华等[42]利用 CloudSat 数据资料研究了东亚地区的云垂直结构，首次计算了气候模式的云辐射过程中表征云的垂直结构特征的抗相关厚度参数，分析该参数的季节变化和空间分布，并讨论抗相关厚度对云辐射强迫计算的影响。杨冰韵等[43]利用 CloudSat 数据产品对云微物理特征量（云中液态水/冰水含量和路径、云滴有效半径等）和云光学参数（云光学厚度等）的全球分布及季节变化进行了统计分析，为推动气候模式及参数检验的发展提供了有效方案。李积明等[44]利用 CALIPSO 激光雷达数据研究了东亚地区云的垂直分布特征，重点分析了云垂直分布特征在各子区域的季节变化特征。研究表明，CPR 具有穿透较厚云层的优势，CALIOP 对于卷云、高积云等光学厚度较小的云层有着精细的探测，CloudSat 和 CALIPSO 协同观测将有效提高云参数反演。Sassen 等[45]探测得到卷云的高度和厚度以及全球时空特征，卷云发生频率为 16.7%。郑建宇等[46-47]利用二级云产品数据分析了 8 种云类及三相态的云量地理分布、纬向垂直分布的季节变化特征以及云层分布概率，另外分析了 3 种不同类型的热带深对流云团的差异。Omar 等[48]介绍了 CALIOP 气溶胶分类算法和激光雷达比的选择方案，给出了气溶胶类型的全球分布。Oliveira 等[49]采用 CALIOP、MODIS、AERONET 和地基激光雷达对 2005—2016 年巴西东北部气溶胶光学特性进行分析，确定了气溶胶的类型。孙雨辰等[50]利用 CALIOP 数据对 6 种气溶胶的全球分布和光学特性进行统计分析，利用其中的退偏比和色比值有效识别大气中的吸收性气溶胶沙尘。另外，中国海洋大学利用 CALIOP 进行了大量海洋风场的反演工作[51-53]。

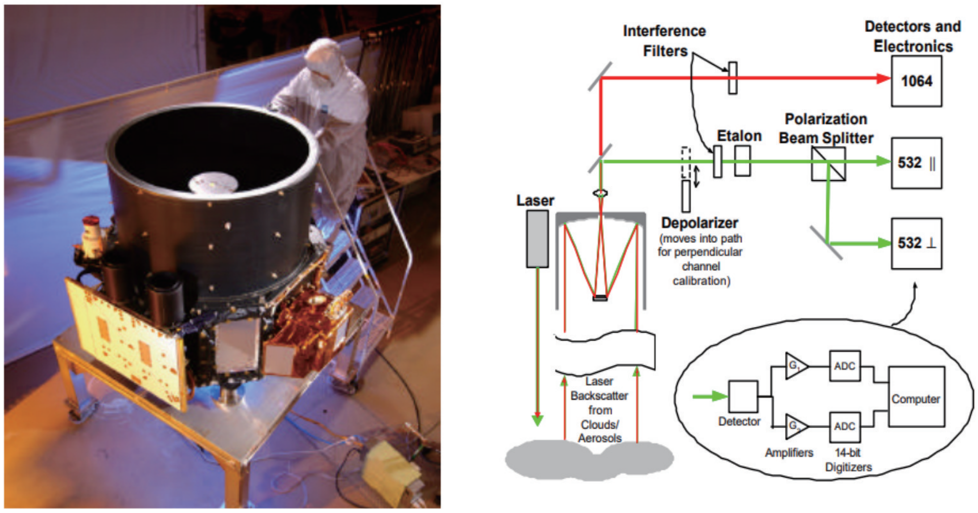

图 2　CALIOP 有效载荷（左）与其功能框图（右）[39]

Fig. 2　CALIOP payload (left) and its functional block diagram (right)[39]

美国 NASA 为了衔接上 CALIPSO 和 EarthCARE 的数据，于 2015 年 1 月将云气溶胶传输系统（CATS）安装在国际空间站（ISS）的日本希望号实验舱——“暴露设施”（JEM—EF）上。CATS 也是迄今为止唯一搭载在空间站上的激光雷达系统，拥有两个高重复频率低能量的 Nd：YVO$_4$ 激光器，采用光子计数方法获得云和气溶胶的垂直分布特性，在 33 个月的在轨运行中，发射了超过 2000 亿个激光脉冲，基于这

些设计参数和运行平台，它具有直接校准1064 nm信号的独特之处[54-55]。CATS有三种工作模式（图3），分别为多波束模式、HSRL模式和紫外模式：多光束模式将来自第一个激光器的能量分为1064 nm和532 nm两个波长，用于探测云和气溶胶的属性，但由于激光电子设备的故障，该模式不能继续使用；HSRL模式使用第二个激光器，采用了HSRL技术，目的是提供更加精确的气溶胶消光系数测量，但该激光器的频率稳定性问题限制了数据的质量；紫外模式同样也使用第二个激光器，在1064 nm和532 nm波长的基础上增加了355 nm波长，为探索355 nm波长在天基激光雷达上的应用积累经验，由于激光光路的故障，CAST在该模式下不能正常工作。CATS首次开机后飞越非洲地区，获得了撒哈拉沙尘高达5 km、卷云延伸超过17 km，以及南非生物质燃烧产生的烟雾的相关结果，与CALIPSO的结果对比一致性较好[56]。CATS在国际空间站上从2015年2月10日运行至2017年10月30日，提供了1064 nm和532 nm大气垂直后向散射廓线，得到了1064 nm波长比以往星载激光雷达更高的信噪比，可直接进行大气校准，对于气溶胶光学厚度，CATS与AERONET、MODIS和CALIOP等星载主被动遥感仪器具有合理的一致性，可利用CATS数据获取全球气溶胶日变化特征[57-58]。

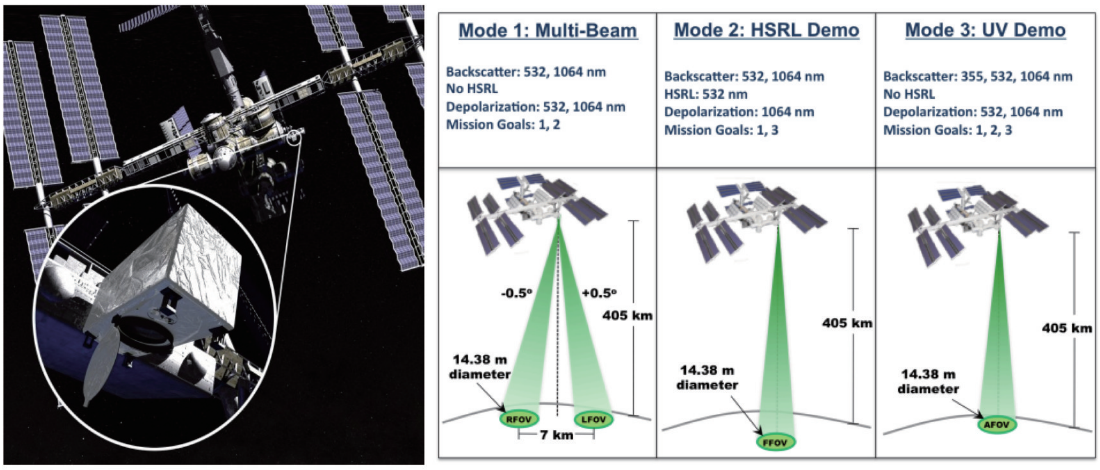

图3 CATS在国际空间站（左）[54]上的三种工作模式（右）[56]

Fig. 3 CATS on ISS (left) [54] in three working modes (right) [56]

为了获取全球大气三维风场信息，ESA于2018年8月22日成功发射了风神（ADM-Aeolus）卫星（图4），其上搭载了大气激光多普勒仪器（ALADIN），是首个获取全球大气风场的多普勒测风激光雷达[59]。星载多普勒测风激光雷达技术可分为相干测风、直接测风和混合体制测风技术，星载多普勒相干测风激光雷达因为研制难度较大，一直未实践[60]。1987年，NASA计划在对地观测系统卫星EOS上搭载激光大气测风仪（LAWS）系统，开创了星载多普勒测风激光雷达的先河，但最终因为预算等原因终止了计划[61]。1998年，NASA再次提出了空间准备相干激光雷达实验（SPARCLE）计划，以及日本邮政省通信研究实验室与美国相干技术公司（CTI）联合准备在国际空间站上搭载多普勒相干测风激光雷达系统（JEM/CDL）等[62-63]。星载多普勒混合体制激光雷达如NASA在2006年提出的混合多普勒风力激光雷达（HDWL）采用2051 nm和355 nm激光进行全球大气风场探测[64]。相对于其他两种体制测风激光雷达，ALADIN采用较为成熟的直接测风激光雷达技术，根据多普勒效应，通过输出脉冲与后向散射信号之间的延迟就能获取大气中不同高度的风速、方向和移动距离等参数。ALADIN由三大部分组成：激光发射器（工作波长为355 nm）、米散射及瑞利后向散射信号接收器组件和直径为1.5 m的卡塞格林望远镜。ALADIN拥有3个通道，其中2个通道采用法布里-珀罗干涉仪（FPI）鉴频技术接收处理大气分子信号，1个通道采用斐索干涉仪分析气溶胶和云的后向散射信号[65-66]。ADM-Aeolus的任务要求为获取20 km左右以下的全球风廓线，对于地表以上2～16 km和16～20 km范围内分别实现2～3 m/s和3～5 m/s的测量精度，每50 km足迹内获得一次平均风速，每小时风廓线数达120条[59]。ALADIN作为目前唯一在轨的星载大气风场探测激光雷达已经运行了4.5年，在2023年4月30日停止工作，但ADM-Aeolus展示了星载激光雷达高精度、强实时性的测风能力，为提高天气与气候预报的准确性、改善大气模式和推进大气动力学研究作出了巨大贡献。

国内星载激光雷达起步较晚。2022年4月16日，我国将气溶胶-云探测激光雷达（ACDL）（图5）、紫外高光谱大气成分探测仪（EMI）、多角度偏振成像仪（DPC）、高精度偏振扫描仪（POSP）和宽幅成像光谱仪（WSI）搭载在大气环境监测卫星（DQ-1）上发射升空（图5）。ACDL同时发射532、1064、1572 nm三波长

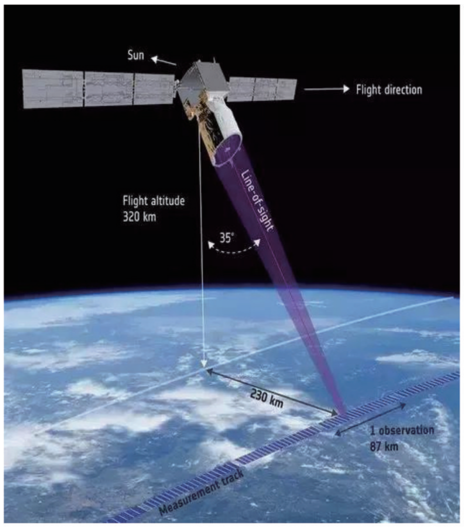

图 4　ADM-Aeolus 探测系统原理[59]

Fig. 4　ADM-Aeolus detection system schematic[59]

双脉冲激光，基于路径积分激光差分吸收（IPDA）和HSRL技术全天时、高精度地获取全球云、气溶胶垂直廓线分布和CO_2柱线浓度等大气环境参数，也是国际上目前唯一在轨运行的主动探测温室气体星载激光雷达[67]。ACDL拥有5个接收通道，分别是532 nm气溶胶高光谱通道、532 nm气溶胶混合平行通道、532 nm气溶胶混合垂直通道、1064 nm气溶胶探测通道和1572 nm二氧化碳探测通道。1572 nm波长重复频率为20 Hz，532 nm和1064 nm波长的重复频率为40 Hz，望远镜口径为1 m，预期CO_2柱线浓度测量精度为1×10^{-6}，气溶胶光学参数为15%的不确定度。ACDL是目前国际上输出波长最多、输出能量最高、激光稳定性最高的星载激光雷达，首次采用IPDA技术获取全球CO_2柱线浓度，也是首次基于碘分子滤波器的HSRL技术探测气溶胶和云的光学参数。EMI具有2600 km的观测幅宽，通过对污染气体光谱信息的识别可获取单日全球的NO_2、SO_2和O_3浓度信息，DPC和POSP在国际上首次运用“偏振交火”的载荷方案实现对气溶胶光学厚度和粒径分布等的观测。DQ-1卫星结合5台主被动遥感仪器协同探测，实现了大气环境要素同步测量，在全球气候变化和空气质量监测方面作出了巨大贡献[68-69]。

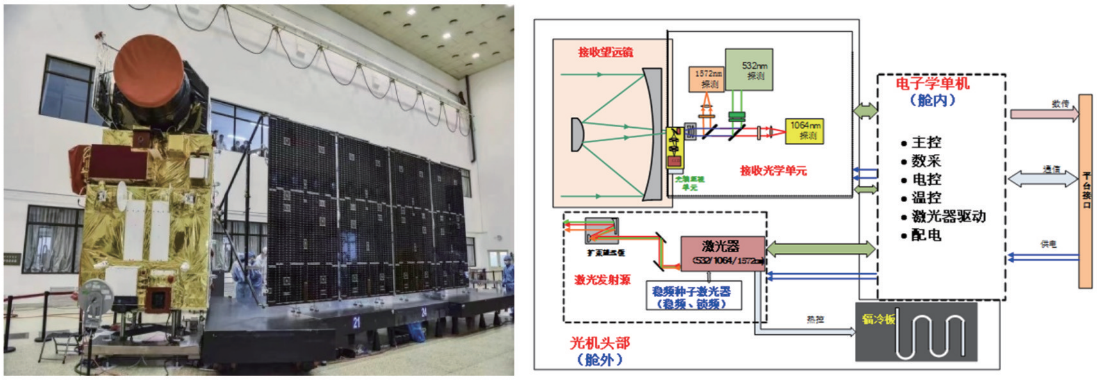

图 5　DQ-1（左）和 ACDL 系统功能图（右）[69]

Fig. 5　DQ-1 (left) and ACDL system functional diagram (right)[69]

2022年8月4日，我国首颗森林碳汇主被动联合观测卫星“句芒号”（CM-1）在太原发射升空，运行在506 km的太阳同步轨道上（图6），轨道倾角为97.4°，覆盖周期为59 d，标志着我国碳汇监测进入遥感时代[70]。陆地生态系统碳监测卫星搭载了多波束激光雷达（CASAL）、多角度偏振成像仪（DPC）、多角度多光谱相机（DMC）和超光谱探测仪（FSI）等多台载荷，以主被动结合的探测方式获取陆地生态系统植被生物量、大气气溶胶和植被叶绿素荧光等信息，为我国在森林冠层高度监测、叶绿素荧光分布和大气环境与气候监测方面提供广泛的应用价值。其中CASAL部分分为植被子系统和气溶胶子系统，分别配置5个1064 nm波长和1个1064 nm/532 nm双波长的激光波束，5个40 Hz的激光波束监测森林冠层高度和结构，以及有效探测云和气溶胶的垂直结构[71-73]。

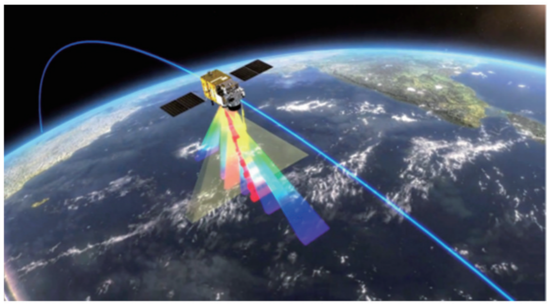

图 6　CM-1 在轨运行[70]

Fig. 6　CM-1 operating in orbit[70]

美国NASA的气溶胶-云-生态系统（ACE）任务在21世纪初被提出，旨在量化气溶胶与云的相互作用，缩小气溶胶-云-降水相互作用的不确定性，评估气溶胶对水文循环的影响，确定海洋碳循环和其他海洋生物过程。载荷激光雷达部分采用三波长（355、532、1064 nm）HSRL技术，另外还包括多光谱偏振成像仪

(MSPI)、用于海洋遥感仪器的水色多通道光谱仪(ORCA)以及双频云雷达(CPR)等[74-76]。

星载全球温室气体主动探测在ACDL成功发射之前，美国、日本等国家以及欧洲的一些国家开展了一系列基于IPDA技术的星载激光雷达任务和机载验证试验。2007年，美国NASA提出了夜间、白天和季节性CO_2排放主动监测计划(ASCENDS)，该计划将测量全球大气中CO_2的浓度，包括陆地和海洋的CO_2的源和汇，且不分季节、纬度、白天和黑夜，以及气压和温度的变化。在计划提出后，美国戈达德航天中心(GSFC)、兰利研究中心(LRC)等多家单位进行了大量的验证分析实验，证明其可行性[7-80]。运行轨道在450 km，望远镜直径为1.5 m，采用HgCdTe雪崩二极管(APD)探测器。该卫星原计划于2025年发射升空，具体计划目前冻结中，设计寿命达3年[81]。

2008年，ESA提出了地球先进空间碳和气候观测任务(A-SCOPE)，以更好地量化全球碳循环，弥补地基组网观测缺陷，发展星载激光雷达技术，在1000 km×1000 km的尺度上，小于0.02 Pg C yr^{-1}的不确定度范围内确定全球CO_2的源和汇。A-SCOPE星载计划同样基于IPDA技术，确定了两种探测波段，分别为1.57 μm(on-line位于6361.2246 cm^{-1}，off-line位于6356.50 cm^{-1})和2.05 μm(on-line位于4875.6487 cm^{-1}，off-line位于4875.22 cm^{-1})，通过选择合适的CO_2吸收谱线，优化CO_2差分吸收值，减小温度的灵敏度和水汽的干扰，对于这两种不同波段选择，配置不同的激光雷达硬件参数，该计划在2014年暂时取消[82-84]。

2017年，法国航天局(CNES)联合德国航天局(DLR)共同研制大气甲烷遥感激光雷达任务(MERLIN)，该激光雷达是唯一搭载的科学仪器，由DLR负责提供，旨在提供覆盖全球的甲烷气体循环信息，完善现有的温室气体监测系统[85]。MERLIN采用1645 nm波段IPDA方法(图7)，吸收峰波长在1645.552 nm处，吸收谷波长在1645.828 nm处，获取高精度XCH_4，目标随机误差优于27×10^{-9}，系统误差优于3.7×10^{-9}[86]。MERLIN运行在500 km高度的轨道上，单脉冲能量为9 mJ，重复频率为20 Hz，设计寿命为3年，卫星发射时间预计在2026年后[87]。

国际上主要的星载激光雷达载荷及其主要技术参数分别如表1和表2所示。

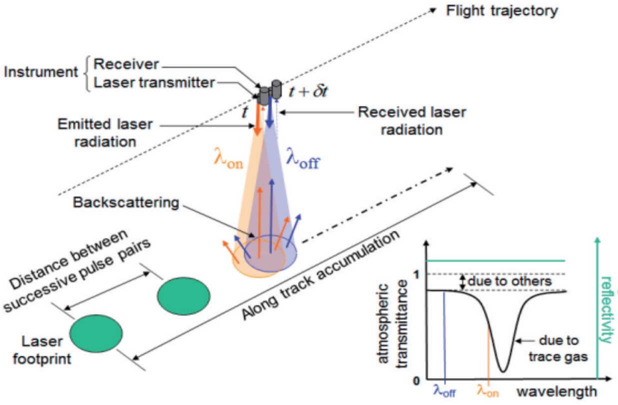

图7　IPDA方法原理图[86]

Fig. 7　Schematic diagram of IPDA method[86]

表1　国际上主要的星载激光雷达载荷

Table 1　Main international spaceborne Lidar payload

Platform Lidar payload	SSD LITE	CALIPSO CALIOP	ICESat GLAS	ICESat-2 ATLAS	ISS CATS	Aeolus ALADIN	DQ-1 ACDL	CM-1 CASAL
Total satellite weight /kg	—	587	970	1514	—	1400	2600	2936
Launch year	1994	2006	2003	2018	2015	2018	2022	2022
Type of orbit	Non-solar synchronous	Solar synchronous	Non-solar synchronous	Non-solar synchronous	Non-solar synchronous	Solar synchronous	Solar synchronous	Solar synchronous
Orbital altitude /km	260	705	600	500	405	320	705	506
Orbital inclination /(°)	57	98.2	94	92	51.64	97	98.135	97.421
Repetition period /d	—	16	91	91	3	7	51	59
Design life	10 d	3 a	3 a	3 a	0.5 a	3 a	3 a	8 a
Target of detection	Clouds, aerosols, etc.	Clouds, aerosols, etc.	Ice, terrain, clouds, aerosols, etc.	Ice, terrain, vegetation, etc.	Clouds, aerosols, etc.	Wind fields, clouds, aerosols, etc.	CO_2, clouds, aerosols, etc.	Vegetation biomass, chlorophyll fluorescence, aerosol, etc.

表2 国际星载激光雷达主要技术参数

Table 2 Main technical parameters of international spaceborne Lidars

Payload	Spatial resolution		Transmitting unit						Receiving unit		
	Vertical	Level	Laser	Wavelength	Single pulse energy	Repeat frequency	Pulse width	Divergence angle	Telescope diameter	Field of view	Photovoltaic conversion
LITE	35 m	740 m	Nd：YAG	355，532，and 1064 nm	500 mJ @532 nm 500 mJ @1064 nm 160 mJ@ 355 nm	10 Hz	—	1 mrad	1 m	—	PMT@ 355 nm，532 nm APD@ 1064 nm
CALIOP	30 m	333 m	Nd：YAG	532 and 1064 nm	110 mJ@ 532 nm 110 mJ@ 1064 nm	20.16 Hz	20 ns	0.1 mrad	1 m	0.13 mrad	PMT @532 nm APD@ 1064 nm
GLAS	Course 170 m Lateral（maximum）15000 m Lateral（minimum）2500 m		Nd：YAG	532 and 1064 nm	75 mJ@ 1064 nm 35 mJ@ 532 nm	40 Hz	5 ns	0.11 mrad	1 m	0.475 mrad@ 1064 nm 0.15 mrad @ 532 nm	SiAPD
ATLAS	Course 90 m Lateral（two strong or two weak）3300 m Lateral（strong and weak）2500 m		Nd：YVO_4	532 nm	Strong：0.12 mJ Weak：0.04 mJ	10 KHz	1 ns	0.024 mrad	0.8 m	83 μrad	PMT
CATS	25 m	15 m	Nd：YVO_4	355，532，and 1064 nm	2 mJ	4 kHz	30 ns	0.03 mrad	0.6 m	110 mrad@ +/ −0.5°	PMT @355 nm，532 nm APD@ 1064 nm
ALADIN	0.25–2.00 km	87 km	Nd：YAG	355 nm	150 mJ	100 Hz	15 ns	12 μrad	1.5 m	22 μrad	CCD
ACDL	30 m	337.5 m	Nd：YAG	532，1064，and 1572 nm	⩾150 mJ@532 nm ⩾110 mJ@ 1064 nm ⩾75 mJ@ 1572 nm	20 Hz@ 1572 nm 40 Hz@ 532 nm 40 Hz@ 1064 nm	⩽50 ns@ 532 nm ⩽50 ns@ 1064 nm ⩽15 ns@ 1572 nm	100 μrad	1 m	0.2 mrad	PMT @532 nm APD@ 1572 nm APD@ 1064 nm

续表

Payload	Spatial resolution		Transmitting unit						Receiving unit		
	Vertical	Level	Laser	Wavelength	Single pulse energy	Repeat frequency	Pulse width	Divergence angle	Telescope diameter	Field of view	Photovoltaic conversion
CASAL	≤30 m	—	—	532 and 1064 nm	73 mJ@ 1064 nm 110 mJ@ 1064 /532 nm	40 Hz	—	40-60 μrad @1064 nm ≤200 μrad @1064/ 532 nm	1 m	—	APD
ACE	—	—	Nd：YAG	355， 532， and 1064 nm	—	—	—	—	1. 5 m	—	PMT @355 nm， 532 nm APD@ 1064 nm
ATLID	40 m	—	Nd：YAG	1064 nm	100 mJ	100 Hz	20 ns	125 μrad	0. 6 m	—	APD@ 1064 nm
EarthCARE	100 m@ 0-20 km 500 m@ 20-40 km	282 m	Nd：YAG	355 nm	38 mJ	51 Hz	25 ns	45 μrad	0. 62 m	75 μrad	PMT @355 nm
MERLIN	—	—	Nd：YAG	1645 nm	9 mJ	20 Hz	20-30 ns	—	0. 69 m	—	APD @1645 nm
A-SCOPE	—	—	Nd：YAG Ho-Tm：YAG	1. 57/ 2. 05 μm	50/55 mJ	50 Hz	—	0. 435/ 0. 2 mrad	1 m	0. 476/ 0. 22 mrad	APD
ASCENDS	—	—	—	1572 nm	—	10 kHz	—	—	1. 5 m	—	APD

3　被动星载遥感探测大气环境参数

3. 1　被动星载遥感探测云

1960年，美国发射了第一颗气象卫星TIROS-1，开启了卫星云遥感观测的新纪元[88]，随后日本、俄罗斯、中国等国家和欧洲的一些国家相继发射众多被动卫星，我国具有代表性的是风云气象卫星[89-90]。风云三号G星于2023年4月16日发射升空，截至目前我国共发射了20颗风云气象卫星，实现极轨卫星和静止卫星的业务化运行。我国新一代极轨气象卫星风云3号D星（FY-3D）于2017年11月15日发射升空，运行在近极地太阳同步轨道上，与FY-3C形成组网观测。FY-3D搭载了10台先进的遥感仪器，包括中分辨率光谱成像仪（MERSI-Ⅱ）、微波成像仪（MWRI-Ⅱ）、红外高光谱大气探测仪（HIRAS-I）等，MERSI-Ⅱ总通道数25个，其中250 m地面分辨率通道6个，其余为1000 m，从而可以获取全球250 m分辨率红外分裂窗区观测资料，红外探测能力较I型大幅提高，光谱覆盖范围为0. 47～12 μm，增加了1. 38 μm短波红外卷云探测通道。MERSI-Ⅱ云顶参数的反演一般采用其中的2个红外分裂窗通道亮温算法，张淼等[91]采用精度更高的一维变分法反演FY-3D/MERSI-Ⅱ云顶温度、高度和压强参数，再利用AQUA/MODIS的云产品数据对FY-3D/MERSI-Ⅱ的水云和厚冰云云顶参数进行精度检验，其中水云云顶高度精度为1. 4 km±1. 8 km。

我国风云四号A星（FY-4A）于2016年12月发射，标志着我国新一代静止气象卫星的新时代到来，使我国首次获得彩色卫星云图[92]。FY-4A上搭载着先进的静止轨道辐射成像仪（AGRI）、干涉式大气垂直探测仪（GIIRS）、闪电成像仪（LMI）和空间环境监测仪器（SEP）。AGRI主要承担获取云图的任务，空间分辨率表现为可见和近红外波段为0. 5～1 km，红外波段为2～4 km，拥有14个通道，中心波长范围为0. 47～13. 5 μm，在观测云的基础上区分云的不同相态，其原理是根据冰云和水云在短波红外1. 6 μm和2. 2 μm处吸收性不同的特性来区分[93]。云的光学厚度和云有效半径影响着云在可见光波段和近红外波段的反射率，

故可利用AGRI的不同通道进行云参数反演。袁锦涵等[94]基于FY-4A/AGRI的一级产品反演了云光学厚度和有效粒子半径，并研究了不同云滴谱对云光学厚度和有效粒子半径的影响，与MODIS反演结果相比一致性较好。

我国高分5号卫星（GF-5）搭载的多角度偏振相机（DPC）主要用于获取云和气溶胶的微物理信息，由中国科学院安徽光学精密机械研究所研制。它的设计借鉴了法国的POLDER/PARASOL，空间分辨率由6.2 km提高至3.3 km，水云和冰云在热红外波段处吸收有差异，粒子形状不同，导致水云和冰云的偏振特性呈现差异，利用多光谱、多角度偏振特点获取全球气溶胶和云的时空分布信息[95-96]。常钰阳等[97]开发了一套云检测、云相态识别和云光学厚度的反演算法，将其应用到POLDER/PARASOL。Li等[98]提出新的云检测方法，通过统计不同时间和地区的不同大气模型和下垫面获得新的动态阈值，从而提高了云识别的准确性，尤其是对于特殊地表类型，在此基础上开展了云相态和云光学厚度反演。

美国NASA研制的中分辨率成像光谱仪（MODIS）搭载在Terra和Aqua卫星上发射升空[99]。MODIS每1～2天获取一次全球数据，拥有36个光谱波段，光谱范围从可见光0.405 μm覆盖到热红外14.385 μm，不同波段的分辨率范围从250 m到1000 m，提高了人类对陆地、海洋和低层大气中的全球动态过程的理解。MODIS被广泛应用到云遥感中，MODIS可以根据可见光和近红外的反射率、红外亮温和反射率构造的指数和量温差等数据来进行云检测，云识别常用8.5 μm和11 μm热红外通道的亮温差进行云相态识别，该方法又称为双光谱法[90，100]。CO_2切片技术常用于MODIS反演云顶参数过程中，当波长范围从13.5 μm到15 μm变化时，CO_2对红外光的吸收能力不断增强，从而导致该波段内的信号受到不同影响，呈现差异[90，101-102]。Platnick等[103]概述了CLDPROP_MODIS和CLDPROP_VIIRS云光学特性数据集算法和传感器件连续性的评估，包括云热力学相位、光学厚度和有效粒径等。

日本气象厅于2014年10月和2016年11月相继发射了Himawari-8和Himawari-9两颗静止轨道气象卫星，上面均搭载了先进葵花探测仪（AHI）。其中Himawari-8的AHI拥有16个波段，中心波长覆盖0.47～13.3 μm，空间分辨率为0.5～2 km。Iwabuchi等[104]利用热红外波段测量数据提取云的宏观、微物理和光学特性，Himawari-8能够捕捉大气中云系统的连续时间的变化，证明了其频繁观测对云系统生命周期研究的实用性。

3.2　被动星载遥感探测气溶胶

气溶胶的星载被动遥感种类繁多，可以大致分为以下几类：多光谱遥感仪器、偏振遥感仪器和多角度遥感仪器[105-106]。多光谱遥感仪器是根据气溶胶对紫外至短波红外多光谱的吸收散射特性进行反演的，常见的星载多光谱遥感仪器包括甚高分辨率辐射仪（AVHRR）、中分辨率成像光谱仪（MODIS）和云与气溶胶成像仪（CAI）。AVHRR搭载在美国TIROS-N卫星、NOAA系列卫星和Metop系列卫星上，AVHRR-3拥有6个光谱通道，早期的AVHRR采用单通道反射比法探测海洋气溶胶的特性[107]。赵柏林等[108]利用NOAA-7搭载的AVHRR的可见光通道，光谱范围为0.58～0.68 μm，得到了晴天渤海上空大气气溶胶光学厚度。随后将双通道算法应用到海上气溶胶反演中。Mishchenko等[109]基于AVHRR数据发现双通道算法可以提供更准确、偏差更小的气溶胶光学厚度的反演，云筛选和校准是造成反演的误差来源。Hauser等[110]利用NOAA-7的AVHRR数据反演得到中欧地区上空20个月的光学厚度，并使用11个AERONET站点进行评估，但不能用于亮地表区域，因为气溶胶信号灵敏度太低。国内学者[111]利用背景合成算法对中国部分陆地区域进行气溶胶光学深度（AOD）的反演，并与MODIS进行对比。

MODIS有7个通道专门用于气溶胶光学特性研究，MODIS提供3种气溶胶光学厚度反演，分别为暗目标（DT）算法、深蓝（DB）算法以及暗目标和深蓝结合（DTB）算法，DT算法根据浓密植被和暗色土壤在红蓝波段反射率低，气溶胶信息相对敏感的特点进行反演，适用于植被表面；DB算法是基于历史数据，采用最小反射率方法构建地表反射率数据库进行AOD反演，适用于陆地AOD反演；DTB算法根据归一化植被指数结合DT与DB算法进行AOD反演[105，112]。毛节泰等[113]利用MODIS数据反演陆地气溶胶再与北京大学地面多波段太阳光度计观测对比，研究发现二者相关性较好。Wei等[114]利用更新后的DT算法对全球的MODIS C6.1版本产品进行验证，研究表明，该版本数据集在不同时空尺度上得到了全面改善。苏玥宇等[115]也利用C6.1版本AOD产品进行验证，对比分析了不同气溶胶类型区域条件下3种算法的精度及误差，更好地了解了MODIS的AOD算法在中国不同类型区域的适用性。

多角度成像分光计（MISR）和MODIS一同搭载在美国Terra卫星上，具备4个可见光或近红外光谱波段及9个角度（±70.5°、±60.0°、±45.6°、±26.1°和0°）的多角度多光谱测量，空间分辨率为275 m～1.1 km[116-117]。Kahn等[118]利用MISR早期AOD算法在陆地和海洋上的性能进行定量评估，与全球分布的AERONET太阳光度计的两年测量记录进行比较，相比其他遥感仪器而言，MISR反演效果已经很好了。MISR除了反演AOD之外，还能分析全球气溶胶类型，为全球气候强迫和气溶胶传输等方面提供参考价值，与MODIS相比一致性很好，海洋上的AOD反演，

二者相关系数约为0.9[119]。张艳婷等[120]联合对比MODIS和MISR数据资料，得到了亚太经济合作组织（APEC）会议前期、期间、后期的AOD和Angstrom指数等气溶胶参数的时空分布特征。

中国科学院安徽光学精密机械研究所自主研制的多角度偏振成像仪（DPC）具有多光谱、多角度和偏振特点，DPC在法国的POLDER上做了很大的改进，性能得到了提高。2013年POLDER结束了探测任务，DPC成为主要的多角度偏振气溶胶探测遥感仪器[95]。高分5号搭载的DPC光谱通道范围为443～920 nm，拥有8个波段，其中3个为偏振波段（490、670、865 nm），5个波段主要用于气溶胶反演（490、670、865、443、565 nm），沿轨最多可获得12个观测角度[121-122]。在利用星载偏振遥感探测气溶胶时，传感器所接收到的信息包括地表和大气的总和，但地表的偏振信息影响DPC反演气溶胶，故地气解耦合尤为重要，提汝芳等[123]基于GF-5的DPC近红外波段865 nm的数据，获取地表多角度偏振反射率数据，针对8种典型地表类型，对比分析了不同模型的双向偏振反射分布函数（BPDF）性能，为估算地表偏振反射率、更好地反演气溶胶参数提供了支持。Li等[124]在一次严重雾霾污染天气中，首次用GF-5/DPC反演气溶胶成分含量和光学辐射性质，通过灵敏度评估了DPC反演的可行性、稳定性和不确定性，该研究使我国在多角度偏振卫星遥感探测方面处于国际先进水平。

3.3　被动星载遥感探测温室气体

被动星载遥感温室气体的原理是基于温室气体在特定波段的吸收特性，根据传感器接收的光谱信息进行定量反演，截至目前世界各国发射可用于探测温室气体的卫星达20多个[125-126]。日本于1996年8月发射了首个可用于温室气体探测的先进地球观测卫星ADEOS，其上搭载的温室气体干涉监测仪（IMG）虽然只工作了8个月，但提供了第一张全球温室气体图，CO_2和CH_4的精度分别为2%和10%[127]。2009年1月日本发射了全球首颗专用于温室气体探测的GOSAT卫星，该卫星配备了两个传感器，碳观测傅里叶变换光谱仪（TANSO-FTS）和云和气溶胶成像仪（TANSO-CAI），TANSO-FTS是基于Michelson干涉光谱技术，探测精度设计技术指标分别为4×10^{-6}（CO_2）和34×10^{-9}（CH_4）。2018年10月日本又发射了GOSAT-2，为GOSAT后继任务，探测精度有很大的提高，CO_2的探测精度设计技术指标为0.5×10^{-6}，CH_4为5×10^{-9}，并且将CO和$PM_{2.5}$纳入了探测范围[128]。

欧洲在2002年3月发射了对地环境观测卫星Envisat-1，搭载大气制图扫描成像吸收光谱仪（SCIAMACHY），探测波段从紫外（约214 nm）到短波红外（约2386 nm），观测模式有天底、临边和掩星三种，SCIAMACHY通过8个通道获取多种温室气体的信息，CO_2和CH_4探测精度分别为3%和10%。Noel等[129]利用SCIAMACHY掩星测量得到的平流层CH_4和CO_2剖面。Frankenberg等[130]获得了2003—2009年全球XCH_4的趋势。

美国NASA于2014年成功发射了碳观测者2号（OCO-2），同年加入了A-Train编队，该任务将揭示CO_2在大气中分布的过程，量化CO_2的源和汇。OCO-2搭载的光栅光谱仪有3个通道（1.61 μm的CO_2弱吸收波段、2.06 μm的强吸收波段和0.764 μm的O_2-A吸收带）[131]，利用地面TCCON站点进行对比验证，OCO-2反演结果一致性较好，绝对中值差小于0.4×10^{-6}[132]。2019年5月，美国NASA发射了OCO-3至国际空间站上，与OCO-2进行协同观测，由于搭载平台差异及OCO-3使用了新的指向镜组件（PMA），引入了新的观测模式，即快照模式，改变了观测数据特征。其科学目标为获得全球高精度的XCO_2和太阳诱导荧光（SIF），提升对全球碳源和碳汇的监测水平[133]。

我国的温室气体探测卫星发展较晚，2016年12月发射了TANSAT碳卫星，成为拥有国际上第三颗具备高精度探测温室气体能力的卫星的国家。TANSAT碳卫星搭载的高分辨率高光谱温室气体探测仪（ACGS）可以获取全球CO_2的浓度，探测原理与OCO系列卫星一致，空间分辨率为1.0 km×2.0 km。TANSAT的结果与TCCON站点、GOSAT和OCO-2对比验证后表现出高精度的探测能力[134-135]。2018年5月高分5号卫星成功发射，高分5号卫星是世界首颗实现对大气和陆地综合观测的全谱段高光谱卫星，其中搭载的温室气体监测仪（GMI）由中国科学院安徽光学精密机械研究所自主研制，首次采用空间外差光谱技术（SHS）获取全球温室气体柱浓度，空间外差光谱技术结合了GOSAT的傅里叶变换光谱仪（FTS）技术和OCO-2的光栅光谱技术，具有极高的光谱分辨率[136]。李勤勤等[137]研究发现，气溶胶类型、地表反射率和地表气压等因素均影响GMI反演CO_2浓度，并利用TCCON站点对GMI反演结果进行验证，反演精度在1%以内。

3.4　被动星载遥感探测大气风场

被动星载遥感大气风场主要以云、水汽和大气成分等为探测目标进行反演，根据探测的原理可以将其分成两类：一是针对云和水汽目标成像，测量目标物在图像中的位移进行风场反演；二是根据大气成分的多普勒频移计算风速，这两类方法分别采用卫星天底观测模式和临边观测模式进行探测[138]。2002年自旋增强可见光与红外成像仪（SEVIRI）搭载在欧洲第二代气象卫星（MSG）上发射升空，SEVIRI通过跟踪云和水汽特征获取大气风场，拥有12个通道，包括11个窄带宽和1个高分辨率宽带通道，具有较高的空间分辨率（4～6 km）[139]。Nerushev等[140]利用SEVIRI探测大气资料对水平风速矢量的计算进度进行了估计，并将结果与独立观测的数据和理论模型进行比较，结果几

乎一致。

基于干涉理论的被动星载探测大气风场的技术主要有Michelson干涉仪测风技术、Fabry-Perot干涉测风技术和多普勒差分干涉仪。干涉仪作为大气风场探测的核心部件，通过接收大气中具有一定多普勒效应的气辉发射线或大气吸收线，将信号转为干涉条纹的变化来反演风场等大气参数[138, 141]。1991年9月由法国和加拿大联合研制的WINDII风成像干涉仪搭载在UARS卫星发射升空，成为全球首个采用Michelson干涉技术的星载被动大气风场遥感仪器，它在视场展宽、步进方式和相位热稳定控制测量风速等方面作出创新，成功探测到80～300 km高度范围的风速、温度和气辉体发射率等。WINDII有两个视场，分别与航天器速度成45°和135°角，因此可以从两个方向观察相同体积的大气，以确定风矢量[142]。WINDII理论设计测风精度为10 m/s，但实际精度可达5 m/s，应用效果显著[143]。

以高分辨率多普勒曾成像仪（HRDI）为代表的星载Fabry-Perot干涉测风技术成功获取了大气风场数据，于1991年搭载在上层大气研究卫星UARS上发射升空。HRDI采用三标准具串联，分辨率为0.05 cm^{-1}，具有很好的白天背景光抑制能力，目标是测量白天平流层（10～40 km）、中间层和低热层（65～110 km）以及夜间中间层（约95 km）的矢量风，探测精度达到5 m/s[144]，水平风矢量是通过测量沿两条视线的分子氧旋转线的多普勒频移来计算的，除了风场参数外，还可以探测温度、云顶高度和一些气溶胶特性。HRDI具有极高的光谱分辨率、较大的光通量和小的温度依赖性等优点[145-146]。

多普勒非对称空间外差技术（DASH）的概念最早由美国Englert团队[147]在2006年提出，是一种全新的大气风场探测技术。DASH干涉仪与Michelson干涉仪在结构上相似，取消了动镜，故机械稳定性更高，构造紧凑，能够对多条谱线同时测量，反演风场精度较高[148]。2019年8月基于该项技术全球高分辨率热层成像干涉仪（MIGHTI）搭载在ICON卫星上成功发射，成为国际上首个星载多普勒差分测风干涉仪。它拥有两个垂直视场，通过同时测量红色（630.03 nm）和绿色（557.73 nm）大气氧原子发射线多普勒频移来探测90～300 km高度区域的风速[149]。为了验证MIGHTI的测量精度，Chen等[150]利用武汉大学的流星雷达和水平风场模型（HWM14）的计算结果与2020年全年的ICON/ MIGHTI卫星数据进行比较分析，结果表明，MIGHTI和他们都表现出强相关性。国外有报道用地基流星雷达和Fabry-Perot干涉仪同MIGHTI数据进行比较验证，在时空匹配大致的情况下结果都比较吻合[151-152]。

4 主被动星载大气探测性能对比与分析

主被动星载大气探测性能对比与分析详见表3～6。

5 总结与展望

卫星遥感是获取全球范围大气参数的有效手段，为全球环境和气候变化提供科学数据支持。被动星载遥感发展起步时间较早，技术更加成熟，可探测的大气环境参数更加丰富，但被动遥感有着不可避免的劣势，如精度不高、高纬度地区覆盖不全、夜间探测数据缺乏等等。激光雷达作为典型的主动遥感设备，具有高精

表3 云遥感探测卫星载荷性能对比

Table 3 Comparison of cloud remote sensing satellite payload performance

Payload	Satellite	Active and passive	Advantage	Disadvantage
MERSI-II AGRI	Fengyun	Passive	With mature development, remote sensing instruments and inversion algorithms are diverse, and Fengyun satellite can form a network detection	Depending on sunlight, the temporal and spatial resolution is insufficient, the difference of the results of different algorithms is questionable, and the inversion effect is poor for complex cloud scenes
DPC	GF-5			
MODIS	Terra/Aqua			
AHI	Himawari			
CPR	CloudSat	Active	Microwave radar can detect the vertical structure of thick clouds due to its strong penetration ability. Spaceborne Lidar has obvious advantages in retrieving cloud top height and high detection accuracy, and has unique advantages in macro and micro parameters of thin clouds	Microwave radar has low spatial resolution, low sensitivity to small-scale clouds, and does not have the detection ability from the ground to an altitude of 1 km, and the limited penetration ability of lidar makes it difficult to retrieve the height of the cloud base, and has limitations for the detection of thick clouds. The sky signal to noise ratio is low
CALIOP	CALIPSO			
ACDL	DQ-1			

表4 大气气溶胶遥感探测卫星载荷性能对比

Table 4 Comparison of atmospheric aerosol remote sensing satellite payload performance

Payload	Satellite	Active and passive	Advantage	Disadvantage
AVHRR	NOAA	Passive	Multi-spectral, multi-angle and polarization means, algorithms and instruments are diverse, the space coverage is large, and the retrievable aerosol parameters are numerous	Depending on sunlight, the spatial and temporal resolution is insufficient, the detection accuracy is limited, and the aerosol profile information cannot be provided
DPC	GF-5			
MODIS	Terra/Aqua			
MISR	Terra			
GLAS	ICESat	Active	It can detect aerosol by quantitative remote sensing, with high spatial and temporal resolution, provide global aerosol vertical structure and high detection accuracy. ACDL′s HSRL system based on iodine filter can obtain aerosol information with higher accuracy without introducing Lidar ratio	CALIOP needs to assume Lidar ratios, increasing sources of error
CALIOP	CALIPSO			
CATS	ISS			
ACDL	DQ-1			

表5 温室气体遥感探测卫星载荷性能对比

Table 5 Comparison of greenhouse gas remote sensing satellite payload performance

Payload	Satellite	Active and passive	Advantage	Disadvantage
SCIAMACHY	Envisat-1	Passive	Various technologies, including Fourier interferometry, grating spectroscopy and space heterodyne spectroscopy technology, strong specialization, and there are specialized passive satellites to detect greenhouse gases, and a variety of observation modes, including nadir, flare, calibration, and target	Data validity is limited by clouds, aerosols, and latitude zones, surface reflectivity and atmospheric component scattering affect detection accuracy, and time and space are limited by night and north and south poles
TANSO-FTS	GOSAT			
3-channel grating spectrometer	OCO			
ACGS	TANSAT			
GMI	GF-5			
ACDL	DQ-1	Active	High detection accuracy, CO_2 detection is expected to achieve 1×10^{-6} accuracy, not easily affected by clouds and aerosols, can achieve all day observation, fill the gap of CO_2 night observation, does not depend on the sun angle, the observation area covers the poles to achieve full latitude observation	The laser has high requirements and is difficult to develop, and the atmospheric parameters affect the high-precision inversion of greenhouse gases

度、高时空分辨率等优点，可弥补被动遥感的不足，目前地基和机载探测大气激光雷达已经相当成熟，星载激光雷达遥感探测是未来发展趋势，从LITE的发射到今天已经发展了近30年之久，可探测的大气参数主要包括云、气溶胶、温室气体、大气风场等。通过对比分析，揭示了大气环境参数主被动星载遥感探测技术的优缺点，从而可根据不同的应用场景和需求，选择合适的探测方式。

1）主被动联合观测、多组分同时测量将是未来全球大气参数探测的研究热点和发展趋势。主被动星载遥感仪器二者优势互补，可增加数据的有效性，实现更高精度的大气环境参数反演，同时增加数据的可对比性。如我国即将发射的DQ-2卫星将激光雷达与高光谱技术结合，将会提高温室气体等参数的反演能力。多组分同时探测有效突破了单一组分探测的限制，可直接进行多参数同步反演。

2）发展全球大气环境参数和大气成分探测是星载激光雷达大气探测的重难点。如星载激光雷达探测大气风场只有ALADIN唯一的激光雷达载荷，虽然测风体制很多，但研制较为困难，国内还未研制出全球风场激光雷达遥感卫星。另外相对于被动卫星遥感来说，还未有专门的激光雷达载荷探测大气温度、湿度、密度和压强等参数，其次星载激光雷达探测大气成分方面需要完善，如未来我国发射高精度臭氧监测卫星搭载

表6　大气风场遥感探测卫星载荷性能对比

Table 6　Comparison of atmospheric wind field remote sensing satellite payload performance

Payload	Satellite	Active and passive	Advantage	Disadvantage
SEVIRII	MSG	Passive	Various detection techniques. The detection range is wide, including the atmospheric wind field in the mesosphere and most of the thermosphere height range. In the observation of tropospheric wind field, spaceborne passive remote sensing has reached the level of operational observation	The detection accuracy and spatial resolution are worse than that of active remote sensing
WINDII	UARS			
HRDI	UARS			
MIGHTI	ICON			
ALADIN	ADM-Aeolus	Active	It can provide the vertical profile of the global atmospheric wind field with high precision and high spatio-temporal resolution, and is one of the best means to obtain the three-dimensional global atmospheric wind field. There are many wind measurement systems that can be developed, and the development potential is great	The detection range is small, and the atmospheric wind profile in the global range of 0-25 km is detected. At present, there is only one kind of ALADIN, the system is single, and there is no Lidar wind measurement satellite in our country

臭氧探测激光雷达和宽波段高分辨偏振成像仪等4台遥感仪器,实现臭氧、PM$_{2.5}$和碳等参数的联合观测;增加甲烷、水汽等气体的探测。

3)一星多载荷以及多卫星组网探测是卫星遥感发展的趋势。将主被动载荷搭载在同一个卫星平台上不仅节省资源,同时提高反演的能力。建立高中低轨组网协同观测,低轨空间分辨率高,能够实现高精度观测,但是存在访问周期长的问题;高轨时间分辨率高,可进行高频次观测,能够实现连续观测,从而完善大气环境参数监测卫星体系。

4)开展新型激光遥感卫星研究。上海航天技术研究院联合中国科学院上海光学精密机械研究所、中国科学院安徽光学精密机械研究所等多家单位拟计划开展激光掩星星座大气观测,实现多类型大气成分垂直观测,进行全球温室气体和污染气体垂直廓线以及大气风速测量。飞秒光丝激光雷达遥感卫星利用飞秒激光大气非线性成丝效应实现紫外至可见宽谱段范围内的主动激光大气成分(O$_3$、SO$_2$、NO$_2$等)高精度探测,相对于被动探测方式来说,精度和垂直探测能力得到大幅提高,相对于传统激光探测,增加了探测谱段和气体种类。大力发展卫星遥感技术将为我国在国际上承担大国责任和增强外交话语权作出科技贡献。

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Comparison and Analysis of Payloads Performance for Active and Passive Spaceborne Atmospheric Detection

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Abstract

Significance Atmospheric environmental parameters directly affect the earth′s ecological environment and climate changes, and even human life and health. For example, aerosols, clouds, and greenhouse gases affect the radiation balance between the sun and the earth through sunlight absorption and scattering, which is an important cause of atmospheric environmental pollution and frequent extreme weather. Additionally, the atmosphere is an aerospace operation area, and environmental parameters such as atmospheric temperature, pressure, density, and atmospheric wind field exert a decisive influence on the design and performance indicators of the equipment. Therefore, the detection of global atmospheric environmental parameters has caught much attention from scholars all over the world.

Satellite remote sensing is an important technical means to obtain global atmospheric environment parameters, and can be divided into active and passive detections. Active detection of its radiation source is to emit different forms of electromagnetic waves to the target. Meanwhile, it does not depend on sunlight and can work day and night. Passive detection of its non-radiation source needs to rely on the reflection of the target object or the electromagnetic wave of the natural radiation source (such as the sun). Compared with the active spaceborne detection technology, the passive detection payloads have a long history, mature technology, and diversified types of remote sensing instruments and detection targets, but there are some problems such as reliance on sunlight, detection time, and regional limitations. The active spaceborne detection technology represented by lidar makes up for these shortcomings, and the active and passive spaceborne remote sensing atmospheric detection technologies are developed jointly to provide strong technical support for the detection of global atmospheric environmental parameters.

Currently, atmospheric environment detection of satellite remote sensing has made great contributions to the detection of clouds, aerosols, atmospheric wind fields, greenhouse gases, temperature, pressure, density, and other parameters, and solved the problems of air pollution, climate changes, and national defense applications. We introduce the development history of spaceborne lidar and focus on the comparative analysis of the advantages and disadvantages of active and passive spaceborne remote sensing payloads for detecting major atmospheric environmental parameters. Finally, the future development trend of atmospheric environmental parameter detection technology in spaceborne lidar and passive remote sensing is summarized.

Progress Since the launch of LITE in the United States, domestic extraterrestrial lidars have developed rapidly for nearly 30 years, and the atmospheric parameters that can be detected mainly include clouds, aerosols, greenhouse gases, and atmospheric wind fields. Although LITE has a short working time, it lays a good foundation for spaceborne lidar atmospheric detection with milestone significance. The ice, cloud, and land elevation satellite (ICESat) carries the geoscience laser altimeter system (GLAS) and is the world′s first earth observation laser altimeter satellite. As a follow-up mission to ICESat, the ICESAT-2 satellite is launched by the national aeronautics and space administration of America (NASA) in September 2018, and is equipped with the advanced topographic laser altimeter system (ATLAS) (Fig. 1). Developed by NASA in collaboration with the French National Space Research Center (CNES), CALIOP is a major breakthrough in the development of spaceborne lidar technology and has been in orbit for 17 years now, far exceeding the expected design. Scientific data are provided for such scientific issues as aerosol-cloud-precipitation interactions, global dust distribution, transport and pollution, and studies on weather and climate changes (Fig. 2). As the only lidar system aboard the space station to date, CATS employs photon counting methods to obtain vertical cloud and aerosol distribution characteristics (Fig. 3). To obtain information about the three-dimensional wind field of the global atmosphere, the European Space Agency (ESA) launched the ADM-Aeolus satellite on August 22, 2018, carrying the Atmospheric Laser Doppler Instrument (ALADIN). It is the first Doppler wind measurement lidar to acquire the global atmospheric wind field. This indicates the high precision and strong real-time wind measurement capability of spaceborne lidar and has made great contributions to improving the weather and climate forecasting accuracy, optimizing atmospheric models, and advancing atmospheric dynamics research (Fig. 4). Domestic spaceborne lidar started late. On April 16, 2022, China launched the aerosol and carbon dioxide detection lidar (ACDL) on the atmospheric environmental monitoring satellite (DQ-1). Based on path integral laser differential absorption (IPDA) and high spectral resolution lidar (HSRL) technologies, atmospheric environmental parameters can be obtained, such as global cloud, aerosol vertical profile distribution, and CO_2 column line concentration in full time and with high accuracy. It is also the only on-orbit spaceborne lidar actively detecting greenhouse gases globally (Fig. 5). Spaceborne lidars such as ASCENDS, A-SCOPE, and MERLIN are also based on IPDA. The platforms and main technical parameters of these spaceborne lidar are shown in Table 1.

There are many kinds of passive spaceborne remote sensing for cloud, aerosol, greenhouse gas, and atmospheric wind field loads, and the inversion algorithms are diverse and mature. In 1960, the United States launched the first meteorological satellite TIROS-1 to open a new era of satellite cloud remote sensing observation. The representative of China is the Fengyun meteorological satellite series. The moderate resolution imaging spectroradiometers (MODIS) in the United States launched on the Terra and Aqua satellites and the Himawari series in Japan show good results in cloud remote sensing. There are many kinds of spaceborne passive remote sensing of aerosols and can be roughly divided into the following categories: multi-spectral remote sensing instruments, polarization remote sensing instruments, and multi-angle remote sensing instruments, such as AVHRR, DPC, MODIS, and MISR. In the passive satellite remote sensing of greenhouse gases, the most representative ones are Japan′s GOSAT series, the United States′ OCO series, and China′s GF-5. The atmospheric wind field of passive spaceborne remote sensing mainly takes cloud, water vapor, and atmospheric composition as detection targets for inversion, including MERSI-Ⅱ, AGRI, DPC, MODIS, and AHI.

Conclusions and Prospects Satellite remote sensing is an effective means to obtain global atmospheric parameters and provide scientific data support for global environmental and climate changes. The development of passive spaceborne remote sensing starts earlier with more mature technology and more abundant atmospheric environment parameters that can be detected. However, passive remote sensing has inevitable disadvantages, such as low accuracy, incomplete coverage of high latitude areas, and lack of night detection data. As a typical active remote sensing equipment, lidar features high precision and high spatio-temporal resolution, which can make up for the shortcomings of passive remote sensing. At present, ground-based and airborne atmospheric lidar detection has been quite mature, and spaceborne lidar remote sensing detection is the future development trend, which has developed for nearly 30 years since the launch of LITE. The atmospheric parameters that can be detected mainly include clouds, aerosols, greenhouse gases, and atmospheric wind fields. Through comparative analysis, the advantages and disadvantages of active and passive spaceborne remote sensing detection technology of atmospheric environmental parameters are revealed. According to different application scenarios and needs, the appropriate detection methods are chosen.

Key words spaceborne lidar; active and passive remote sensing; optical payload; atmospheric environmental parameters; atmospheric detection