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塑造智慧变革

北京
国家会议中心
2018年
9月10-12日
2018.hexagonchina.com.cn

TerrainMapper: breakthroughs in Leica airborne LiDAR technology
TerrainMapper:徕卡机载激光雷达技术的新突破

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11th Sep, 2018

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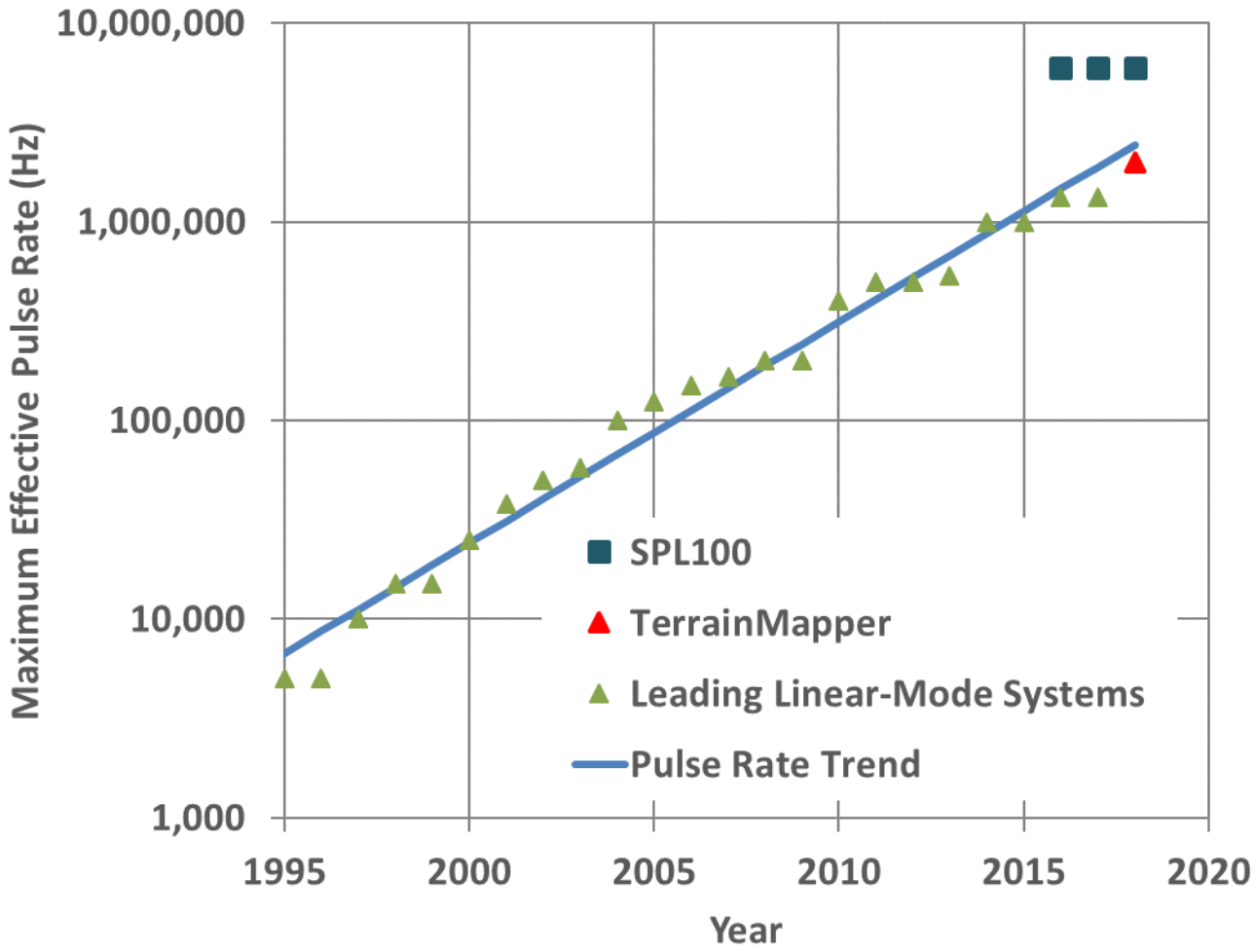
How airborne topographic LiDAR has developed to meet ever-changing needs
机载陆地激光雷达是如何发展来满足不断变化的需求

- Historical perspective and the ALS-series LiDAR products
- Introduction to TerrainMapper
- Performance and benefits of the TerrainMapper sensor
- Performance and benefits of the HxMap workflow
- Recommendations for employing the latest linear-mode LiDAR technology

- 历史发展及ALS系列激光雷达产品
- TerrainMapper产品介绍
- TerrainMapper传感器性能及优势
- HxMap后处理软件的性能及优势
- 最新线性激光雷达技术的选用建议

History of productivity improvement in airborne topographic LiDAR
机载陆地激光雷达的生产力提升历史

- Driver is reduced cost per data point
- Data acquisition (flight operations) cost is key contributor
- More points/second ➔ lower flying costs
- Therefore, effective pulse rate is a good measure of productivity
- Effective pulse rates have doubled every ~2.6 years
- R^2 = 0.9825!!!
- During this same time, accuracies have improved from ~30cm to as good as 3cm!!!
- 降低每个数据点的成本为驱动
- 数据采集（飞行）是主要成本
- 每秒钟获取更多的点➔更低的飞行成本
- 因此，有效脉冲频率是生产力的重要指标
- 有效脉冲频率每2.6年翻一倍
- R^2 = 0.9825!!!
- 同时，精度水平也从~30cm提升到3cm！！！



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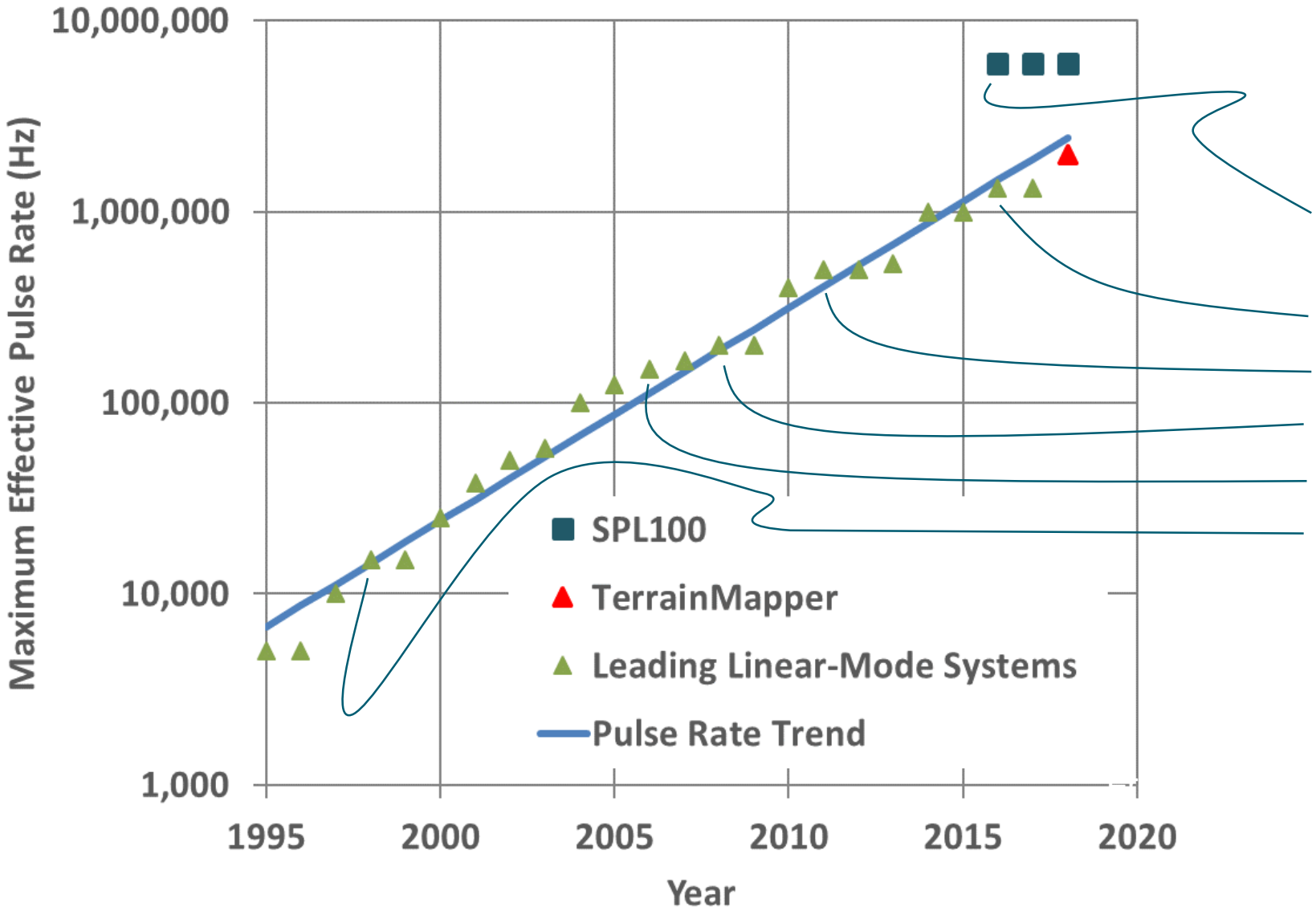
Key innovations along the way drive system productivity
系统产品力提升过程中的重要变革



Single-photon technology

Linear-mode technology (ALS-series)

- Ungated MPiA, FWD-based systems
- Multiple-output
- Gated MPiA
- Fiber lasers
- Diode-pumped lasers

单光子技术

线性激光技术（ALS系列）

- 无测距范围限制的MPiA，全波形系统
- 多激光器
- 有测距范围限制的MPiA
- 光纤激光
- 二极管激光

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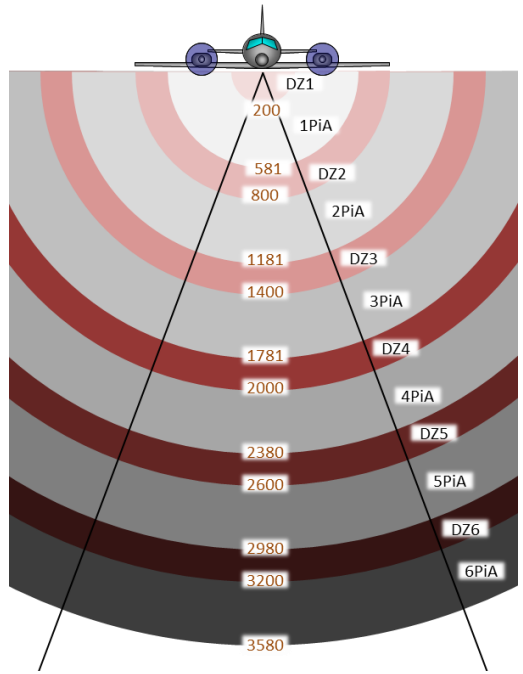
Gated MPiA: a major limitation
有测距范围限制的MPiA：重大阻碍

- Think of MPiA zones as “rings” or “bands” of operation
- In gated MPiA systems, each MPiA zone consists of two components
  - “Dead zone” (“DZn” in illustration) where system is “blind” while laser fires
  - “nPiA”, representing ranges from the nth pulse in the air
- The challenge: all range variations must be accommodated within a single MPiA zone, and these variations are caused by:
  - Planning DEM inaccuracies
  - Real-time GNSS navigation error
  - Pilot’s inability to stay perfectly “on line”
  - Increases in slant range (even on flat terrain) from nadir to FOV edge
  - Terrain elevation variation within the FOV
- Example at right from ALS-series instrument @ 250 kHz
  - Each MPiA zone is 600m range, but
  - “Dead zone” is ~200m “thick”, leaving only 600 m to accommodate all the variations described above
- At 2.0 MHz, each MPiA zone is only ~75m “thick”!

- 多脉冲区间可以想象成数据获取过程中的“圆圈”或“条带”
- 在有测距范围的多脉冲系统中，每个多脉冲区间包括两个组成部分
  - “无信号区间”（右图“DZn”）在激光发射时系统“失明”
  - “n次脉冲区间”，代表n次空中脉冲的测距范围
- 面临的挑战：所有测距变量必须容纳在单个多脉冲区间中，这些变量能够被以下因素造成：
  - 设计时不准确的DEM
  - GNSS实时导航误差
  - 飞行时的偏航误差
  - 航带正下方至边缘斜距的增加（即使平地）
  - 视场角范围内的地形高差
- 右图是ALS系列产品图例@250kHz
  - 每个多脉冲区间约600m，但
  - “无信号区间”约200m“厚”，使得仅有600m范围留给如上描述的测距变量
- 脉冲频率为2.0MHz时，每个脉冲区间仅有约75m“厚”



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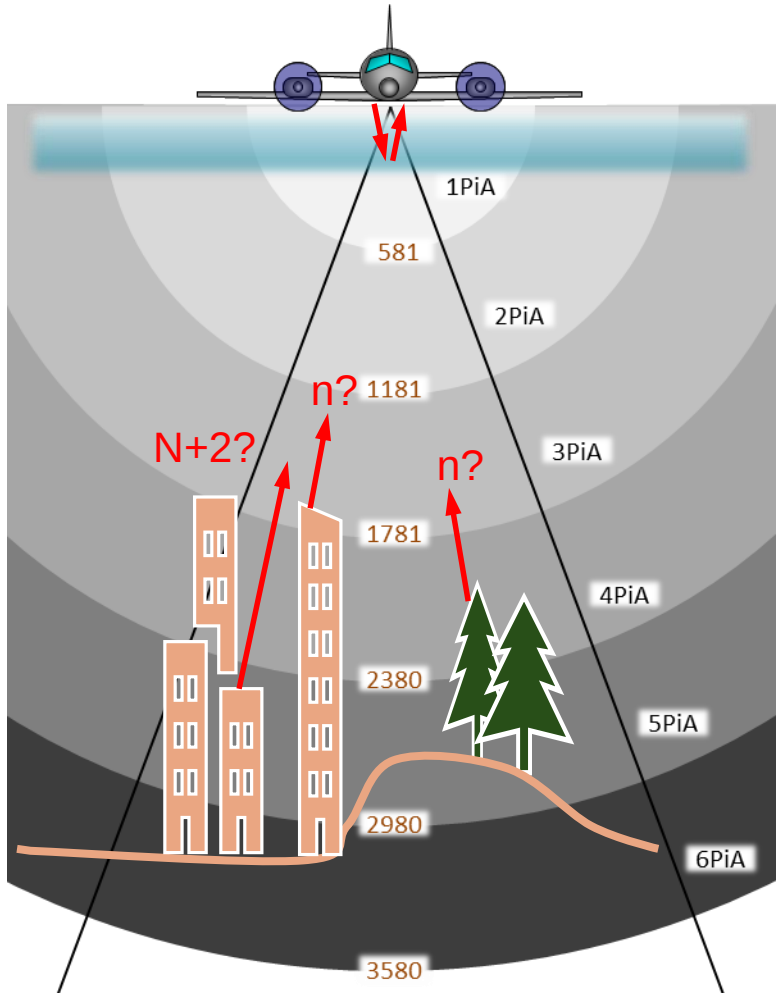
Gateless MPiA: solving challenges in creating a high-pulse-rate system
无测距范围限制的MPiA：解决了制造高脉冲频率设备的阻碍

- Eliminating “dead zones”: Receiver must be able see return signals even when laser is firing
- Ambiguity resolution: Must be able to determine which return pulse comes from which laser shot
- Atmospheric backscatter: Must be able to differentiate atmospheric backscatter returns from real target returns
  - Backscatter otherwise gets blended with real targets and becomes difficult-to-filter near-ground noise
- Faster pulse rate = smaller MPiA zones
  - Terrain variation and building/tree heights can easily span multiple zones
  - In urban environments, “zone skipping” can occur ➔ return pulses from building tops in MPiA zone *n*, while returns from next lase shot are on roadway, in zone *n+2* or *n+3.* Simple tracking algorithms are not enough.
- Additional challenge: Fast pulse rates demand fast scan rates
  - Keeps point spacing similar in along-track and cross-track directions
  - Combination of higher flying heights and fast scan rates results in focal spot wander that must be dealt with

- 消除“无信号区间”：接收器必须在激光发射时也能接收回波
- 不定性消解：必须能够区分回波属于哪次激光脉冲
- 大气散射：区分大气散射和真实回波
  - 否则散射将和真实回波混淆而成为难以滤波的近地噪声
- 更快的脉冲频率=更小的多脉冲区间
  - 地形起伏或楼房/树高度容易跨过多个区间
  - 城市环境中，“跳区”情况➔楼顶回波信号在脉冲区间n，然而下一束脉冲回波还在途中，如区间n+2或n+3，简单的跟踪算法并不理想。
- 其他挑战：更快的脉冲频率需要更高的扫描频率
  - 保持航向和旁向点分布均匀
  - 高航高和高扫描频率导致激光焦点漂移，而这个问题必须解决



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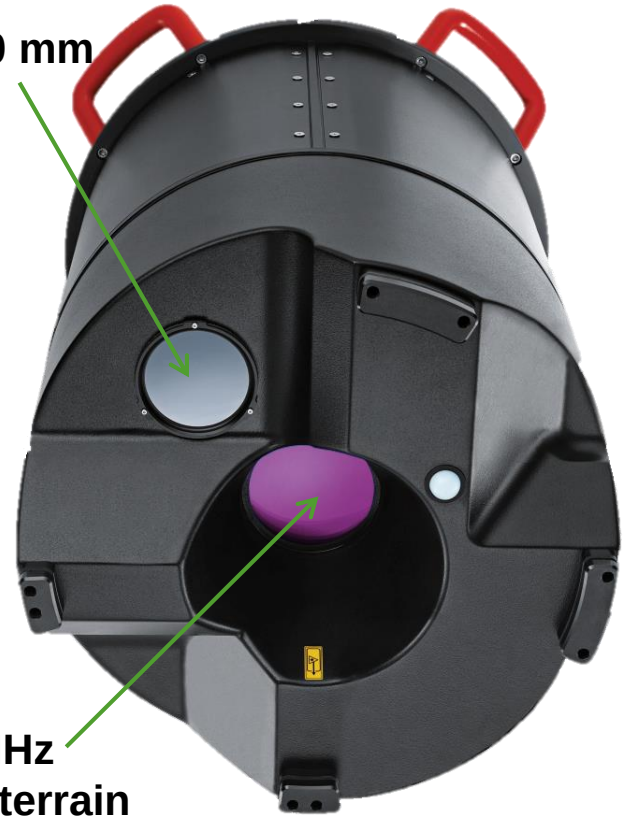
TerrainMapper: New generation linear-mode LiDAR
TerrainMapper：新一代线性激光雷达

- TerrainMapper brings the ALS portfolio into a completely new generation
- LiDAR sensor based heavily on CityMapper LiDAR development, but with materially improved capability
  - Pulse rate to 2.0 MHz @ 2000 m AGL
  - Flying height to 5500 m AGL
- Cylindrical design adapted for installation in the Leica PAV100 stabilised mount
- Available in two different variants
  - TerrainMapper-L: LiDAR only
  - TerrainMapper-LN: LiDAR + NADIR RGBN camera
- Most flexible and best performing linear-mode LiDAR

- TerrainMapper将ALS产品线引入全新时代
- 激光器基于CityMapper研发，但包含了重要的性能提升
  - 脉冲频率2.0MHz@2000mAGL
  - 航高高达5500mAGL
- 圆桶机身设计便于徕卡PAV100陀螺稳定平台安装
- 包含两种不同配置
  - TerrainMapper-L: 仅激光器
  - 最灵活和最强性能的线性激光雷达

NADIR Camera
- **80 MP**
- **RGB+NIR**
- **80 mm or 50 mm lens**



LiDAR
- **2 MHz**
- **All terrain**
- **300 m to 5,500 m AGL**

TerrainMapper: Unique performance
TerrainMapper：独一无二的性能

- Highest collection efficiency among linear mode LiDAR: collection rate up to 2 MHz
- Capable over all terrain with gateless MPiA
  - Capable of handling reflections from up to 35 MPiA zones simultaneously
  - Easily handles the most complex terrain, from urban mapping to mountanous areas, delivering a seamless dataset over huge terrain height variations, all without reducing pulse rates
- Most flexible for all LiDAR applications
  - Flying heights from 300 m to >5,500 m AGL
  - Remarkable sensitivity allows collection rates of USGS QL0 data, (8 pps, <5 cm $RMSE_z$) at up to 500 km^2 / hour
- Outstanding accuracy
  - Full waveform LiDAR system with on-board real-time waveform-to-range processing
  - Capable of extracting of up to 15 returns per oubound LiDAR pulse, with a minimum return separation of less than 50 cm
  - LiDAR waveform attributes stored with all data, full waveforms at downsampled rates optional

- 业界最高的线性激光雷达效率：每秒钟200万次点云采集
- 无测距范围限制MPiA适用于所有地形
  - 同时可进行35次多脉冲区间的回波采集
  - 轻松应对复杂地形，不管是城市还是山区，无缝获取大高差地形数据且没有脉冲损失
- 最灵活的激光应用
  - 飞行高度从300m至>5500mAGL
  - 无与伦比的灵敏度满足以500km^2 / 小时进行USGS QL0的数据获取（8点/m^2，<5cm RMSEz）
- 出色的精度
  - 实时在线波形-测距处理，全波形激光器
  - 每次激光脉冲最高可获取15次回波，最小回波距离小于50cm
  - 激光波形属性存储于数据中，可选低采样率全波形

Milan, Italy, fused elevation and intensity data
意大利，米兰，高程强度显示数据

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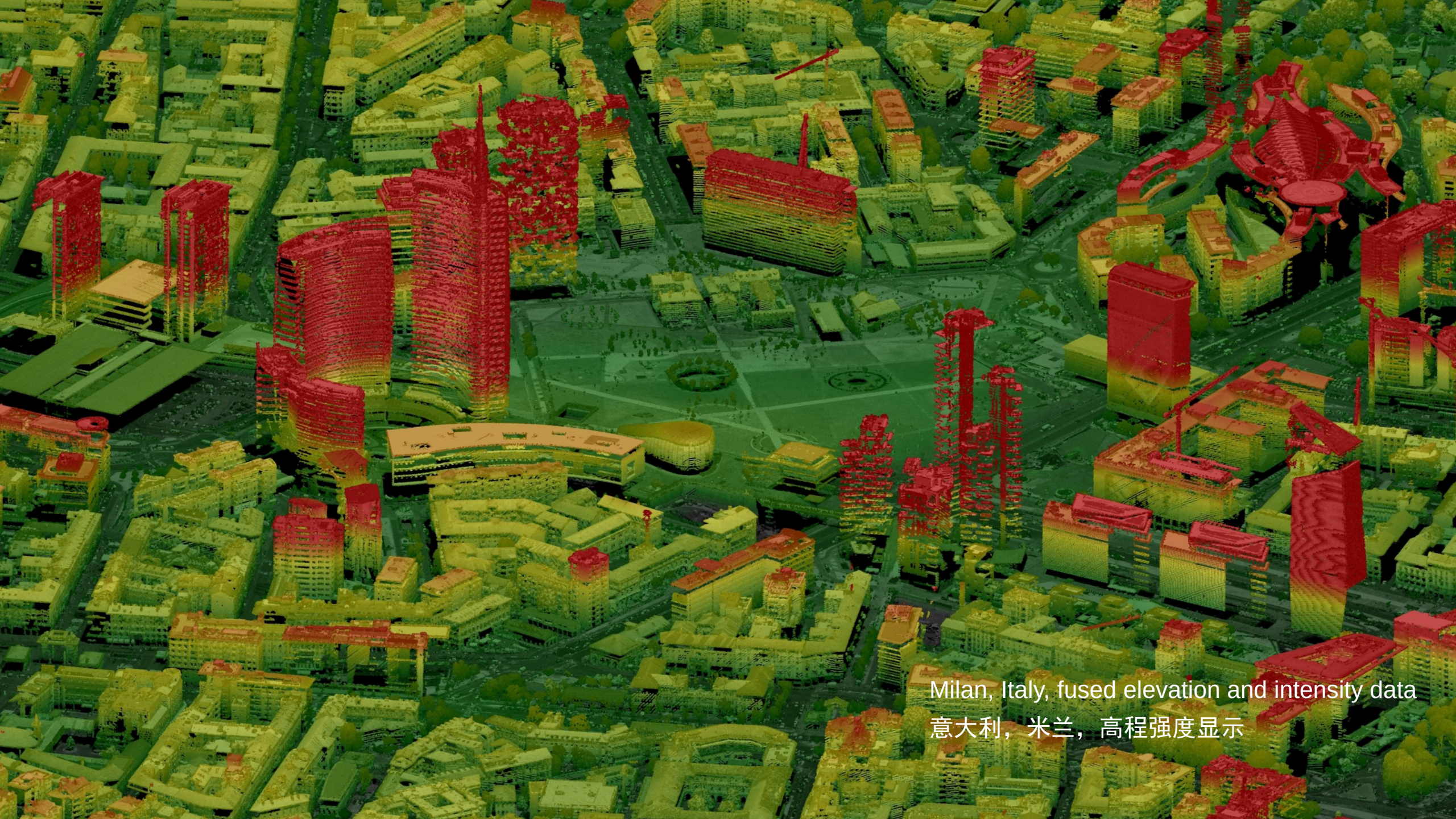
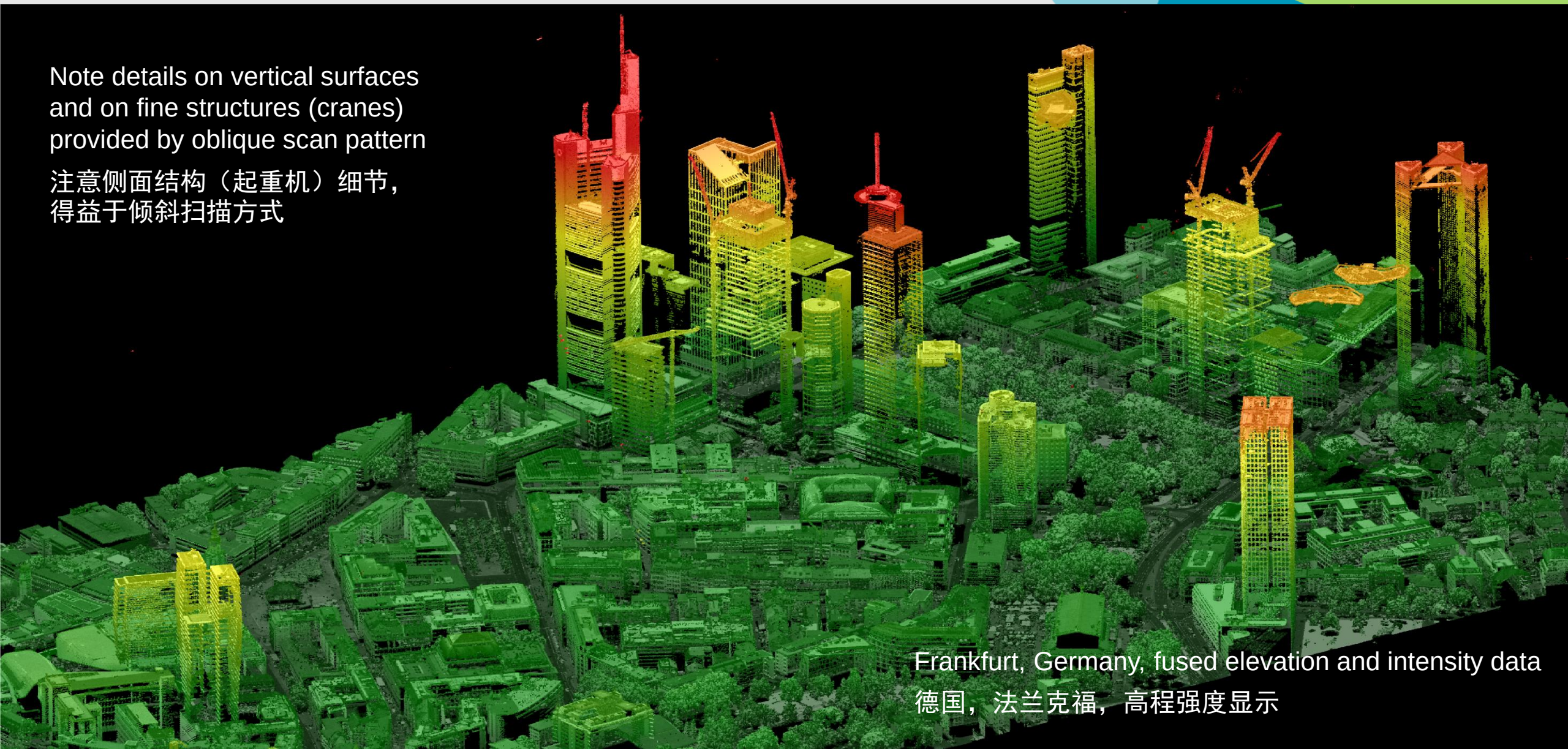


Milan, Italy, fused elevation and intensity data

意大利，米兰，高程强度显示

Note details on vertical surfaces and on fine structures (cranes) provided by oblique scan pattern

注意侧面结构（起重机）细节，得益于倾斜扫描方式



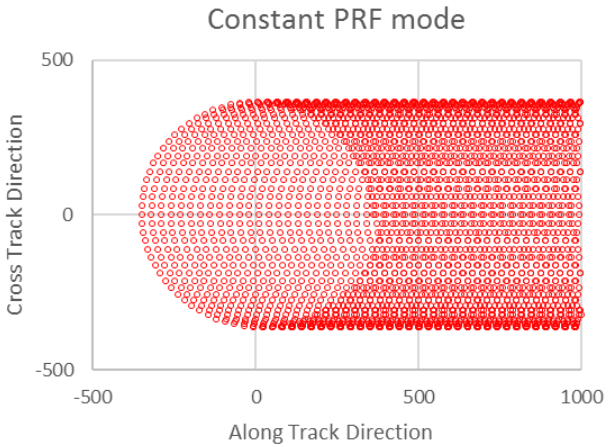
Frankfurt, Germany, fused elevation and intensity data

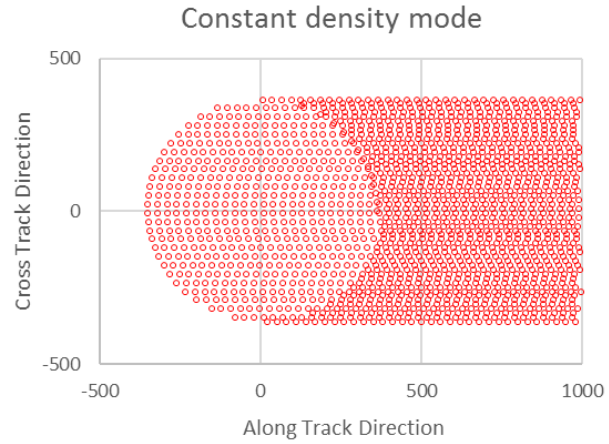
德国，法兰克福，高程强度显示

Constant Density Mode: TerrainMapper exclusive!
恒定点密度模式：TerrainMapper独有！

- Constant PRF mode
  - Uses constant PRF everywhere in scan
  - Cross-track spacing gets smaller toward FOV edge
  - Density lowest at nadir and highest at FOV edges (note denser red color in graphic)
- Constant density mode
  - Uses same PRF as constant PRF mode at nadir, but reduces PRF approaching FOV edge
  - Cross-track spacing stays near constant across FOV
  - Density stays constant approaching FOV edge (note consistent color in graphic)
- Benefits
  - Full swath with same density as at nadir, but with ~35% fewer points than in constant PRF mode
    - Less data to store
    - Less data to process
  - Filtering and classification algorithms work best with minimal variations in point density

- 恒定脉冲频率模式
  - 使用恒定脉冲频率进行扫描
  - 旁向点距在FOV边缘变小
  - 点密度航带中央最低，边缘最高（注意图中深红色）
- 恒定点密度模式
  - 航带下方脉冲频率和恒定脉冲频率模式一致，但在边缘降低PRF
  - 旁向点距基本恒定
  - 点密度保持恒定（注意图中颜色基本一致）
- 优势
  - 航带内点密度和正下方一致，但比恒定脉冲频率模式少约35%点
    - 更少的数据存储
    - 更少的数据处理
  - 点云滤波和分类算法在点密度差异最小时最有效





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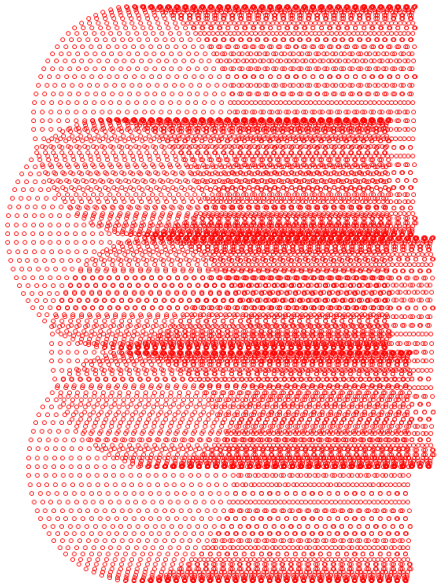
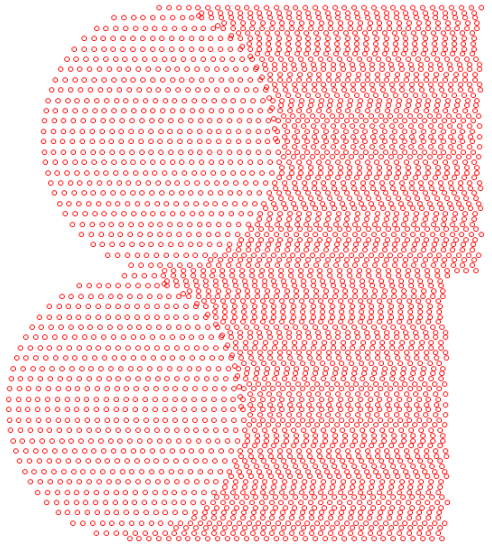
Use cases for constant PRF and constant density modes
恒定脉冲频率和恒定点密度模式应用案例

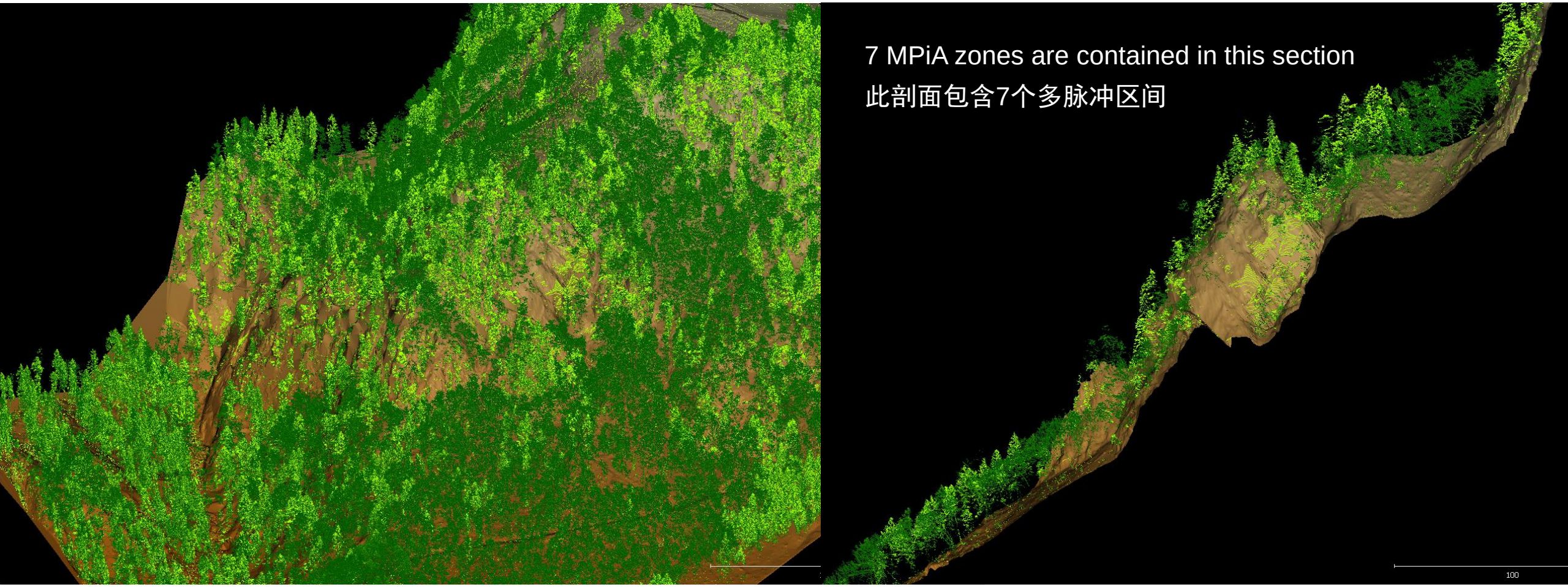
- Use constant PRF mode if using high side overlap (>50%)
  - Low density in nadir area filled in by high-density edges of adjacent flight line
  - Maximizes overall density
- 高重叠度（＞50%）使用恒定脉冲频率方式
  - 航带下方低点密度需要临近航线边缘补偿
  - 整体点密度最大



- Use constant density mode if using low side overlap (<50%)
  - Even density and more regular point distribution may help filtering algorithms
  - Reduced data volume
- 低重叠时(<50%)使用恒定点密度模式
  - 均匀的点密度和分布有助于滤波算法
  - 减小数据量



Robust ungated MPiA allows extreme pulse rates in extreme terrain
可靠的无测距范围限制MPiA允许在大高差下使用更高脉冲频率



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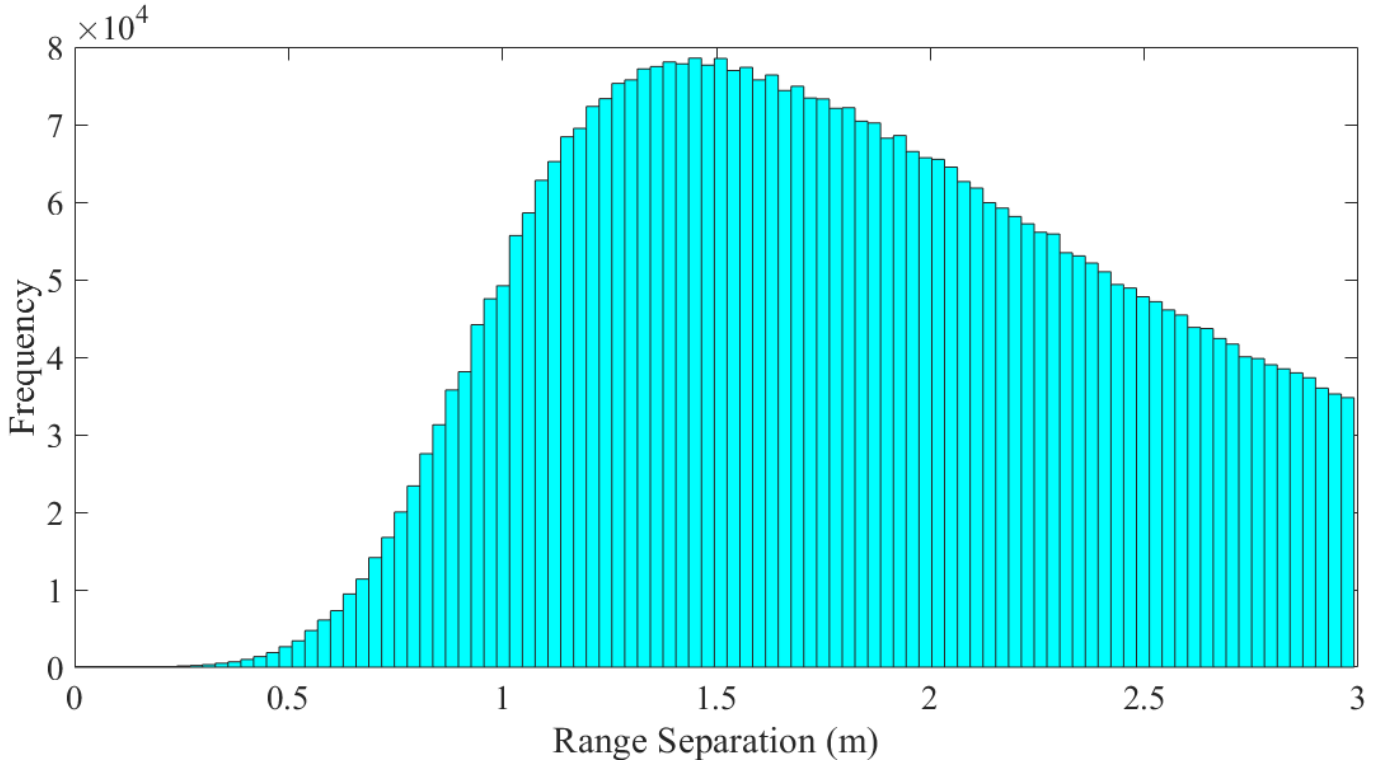
Small minimum vertical separation; key to detail in cluttered environments
更小垂直分辨率： 获取复杂环境细节的关键

- TerrainMapper can differentiate targets with <0.5m vertical separation
- Enhances tree canopy detail
- Differentiation of closely-spaced power lines
- Enabling technologies
  - Short-pulse-width laser
  - Fast digitizer

- TerrainMapper能够分辨高差＜0.5m的目标
- 更多的树冠细节
- 分辨小间距电力线
- 实现技术
  - 短脉冲宽度激光
  - 更快的电路设计



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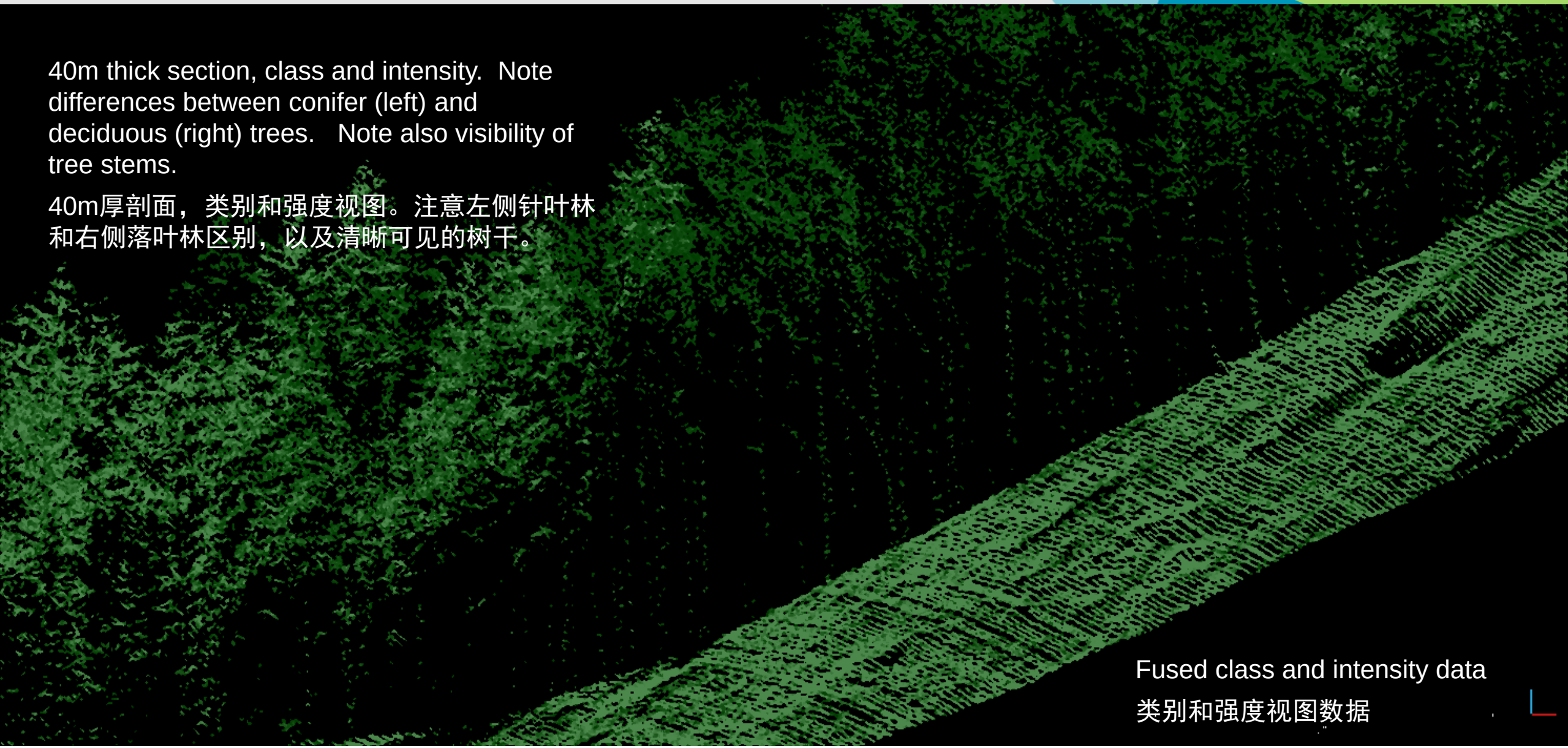


40m thick section, class and intensity. Note differences between conifer (left) and deciduous (right) trees. Note also visibility of tree stems.

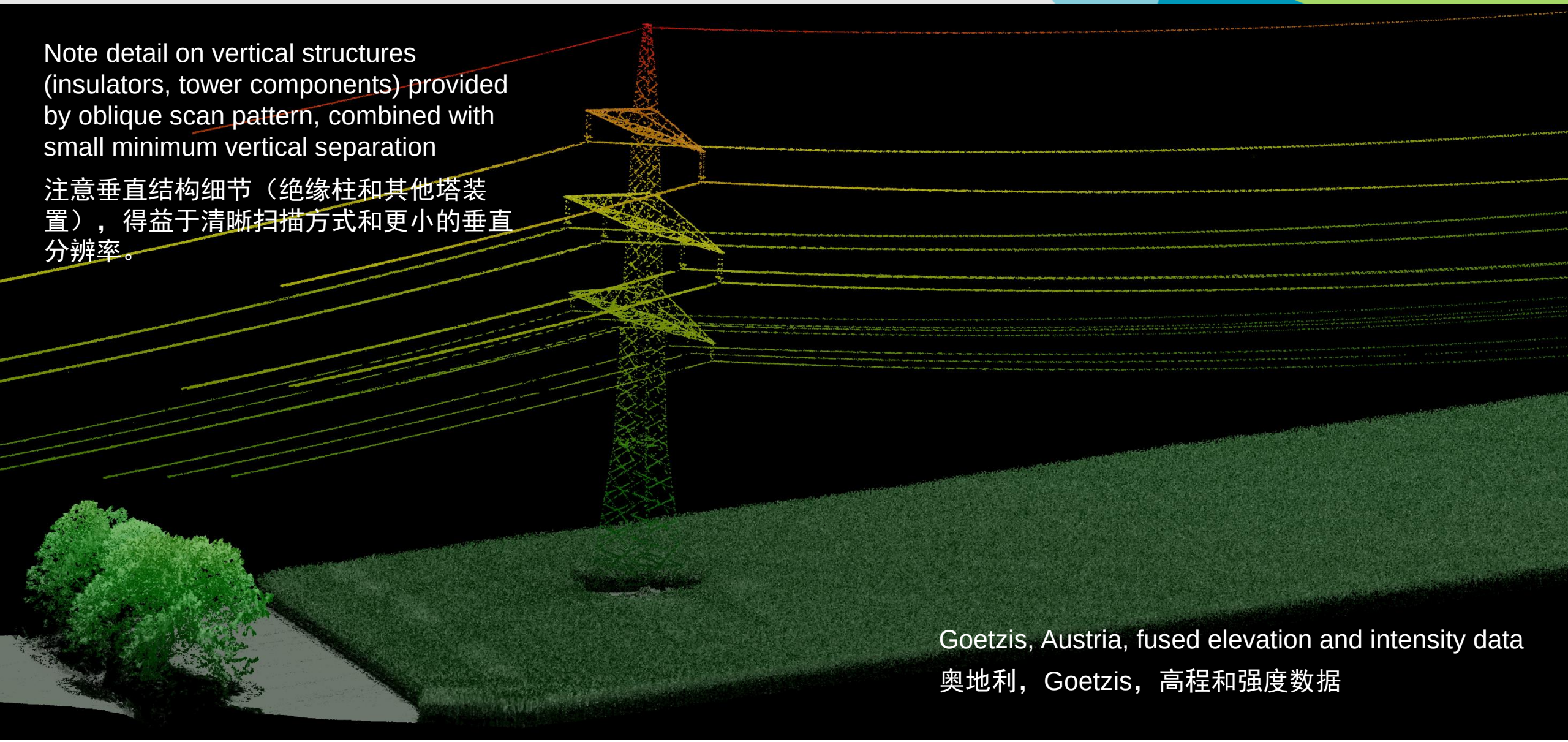
40m厚剖面，类别和强度视图。注意左侧针叶林和右侧落叶林区别，以及清晰可见的树干。

Fused class and intensity data

类别和强度视图数据

Note detail on vertical structures (insulators, tower components) provided by oblique scan pattern, combined with small minimum vertical separation

注意垂直结构细节（绝缘柱和其他塔装置），得益于清晰扫描方式和更小的垂直分辨率。



Goetzis, Austria, fused elevation and intensity data

奥地利，Goetzis，高程和强度数据

TerrainMapper Calibration Results: 2 overlapping flight lines @ 1,000 m AGL
TerrainMapper检校结果：2条重叠航线@1000mAGL

M003_1000C_vs_M004_1000C

392982 valid patches with size of 2 m found. Only patches with standard deviation < 0.05 m and minimum of 5 points are included.

Color	Limits [m]	Number of patches	Proportion of total number of patches [%]
	<=0.03	391084	99.52
	0.03-0.05	1830	0.47
	0.05-0.1	56	0.01
	>0.1	12	0.00

Vertical difference

99.5% of patches have vertical match within 3 cm/99.5%的块片高程误差<3cm

TerrainMapper Calibration Results: 2 overlapping flight lines @ 2,000 m AGL
TerrainMapper检校结果：2条重叠航线@2000mAGL

RealTerrain

H001_2000C_vs_H002_2000C

1387325 valid patches with size of 2 m found. Only patches with standard deviation < 0.05 m and minimum of 5 points are included.

Color	Limits [m]	Number of patches	Proportion of total number of patches [%]
	<=0.03	1343186	96.82
	0.03-0.05	41780	3.01
	0.05-0.1	2326	0.17
	>0.1	33	0.00

96.8 % of patches have vertical match within 3 cm/ 96.8%的块片高程误差<3cm

Vertical difference

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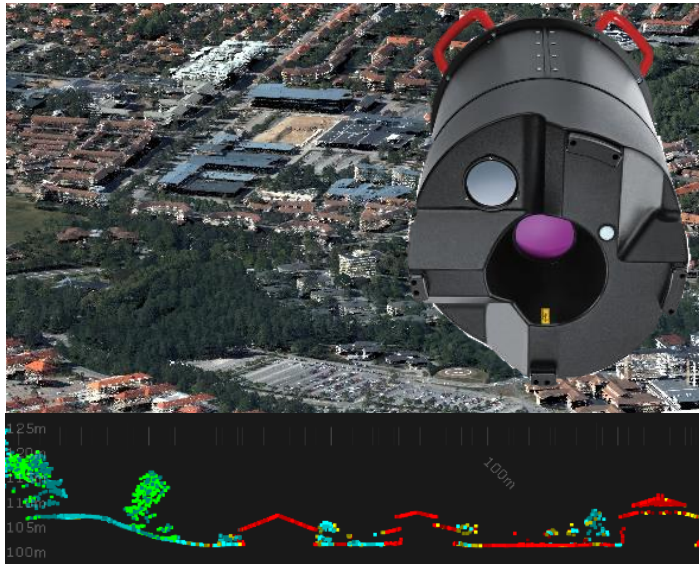
TerrainMapper: Optimal tool for regional mapping projects
TerrainMapper：区域测量的最佳工具

- Highest efficiency
  - Up to 2 MHz measurement rate
  - USGS QL0 data (8 points/m^2, <5cm RMSEz) @ up to 500 square km / hour
- Highest accuracy
  - <5 cm RMSEz @ 2,000 m (6,500 ft) AGL
- Any terrain
  - Seamless data from up to 35 simultanious MPiA zones
- Even point distribution
  - Eliminating point density variation between center and edges of scan
  - Stabilized mount elminates flight trajectory deviations
- The flexibility to capture any LiDAR project
  - 300 m – 5,500 m AGL
  - Variable FOV
  - High scan rates regardless of FOV
- Efficient multisensor workflow
  - Highest data throughput in a production environment
  - The tools you need: calibration, quality control, colorisation and end product generation

- 最高效
  - 高达2.0MHz测量频率
  - USGS QL0数据（8点/m²，＜5cm RMSEz）@500平方km/小时
- 最高精度
  - <5 cm RMSEz @ 2,000 m (6,500 ft)
- 全地形
  - 高达35次多脉冲同时无缝获取
- 均匀点分布
  - 消除航带边缘和下方的密度差异
  - 陀螺稳定平台消除航线轨迹偏差
- 最灵活的应用
  - 300 m – 5,500 m AGL
  - 可调FOV
  - 任何FOV都可以使用最高扫描频率
- 高效的多传感器后处理
  - 最高效的数据生产
  - 提供功能：检校、质检、着色和最终产品生产



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