Vertical Constraints **Voxel Map Multi-Scale Preprocessing** Management Registration **ICP** Motion-Hash voxel Robust normal Range outlier predicted indexing equations removal initialization Bounded voxel Frame-to-frame z-step gating buckets alignment Uniform voxel downsampling Sliding-window Frame-to-local Gain-based refinement selection pruning Cleaned frame neighborhood Stopping and Frame-level z output fallbacks search clamp **Outputs LiDAR Input** Final pose Updated local Raw LiDAR Time-stamped

frames

scans

LiDAR

estimate

maps

Global map