Efficient computation of object precision for terrestrial laser scanner viewpoint planning

Photogrammetric Computer Vision Workshop

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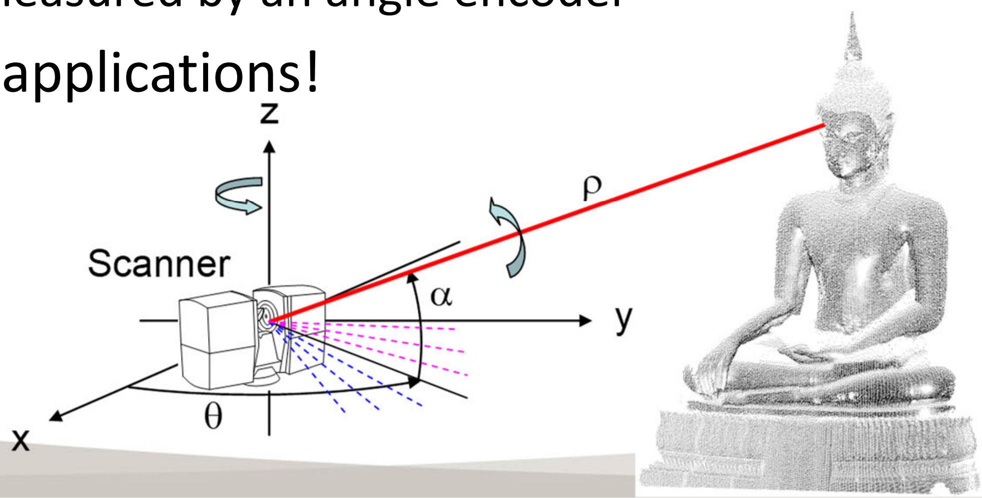
http://www.clker.com/clipart-24980.html

Terrestrial Laser Scanners (TLSs)

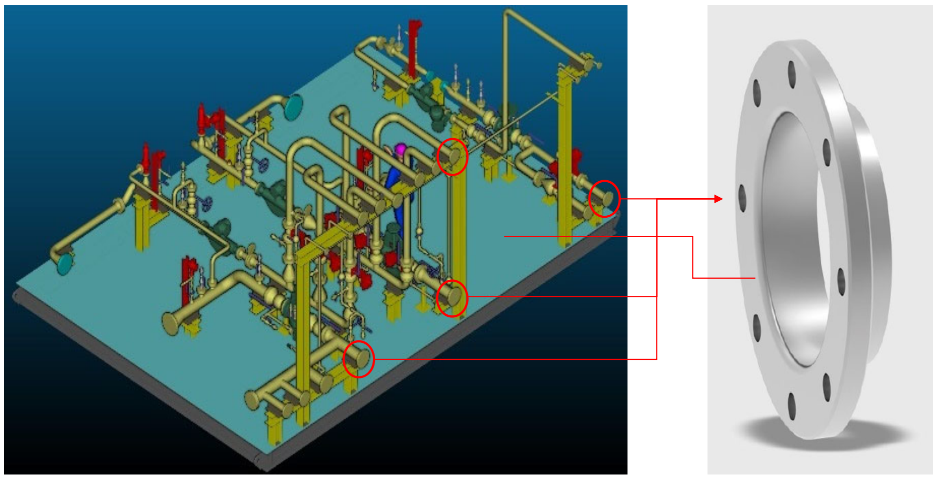
- Reflector-less, tripod-mounted sensors that collect 3D point cloud data from a static platform
  - Range, ρ, measured in equal increments of arc by pulse time-of-flight or phase difference
  - Horizontal direction, θ, measured by an angle encoder
  - Elevation angle, α, measured by an angle encoder
- Many measurement applications!

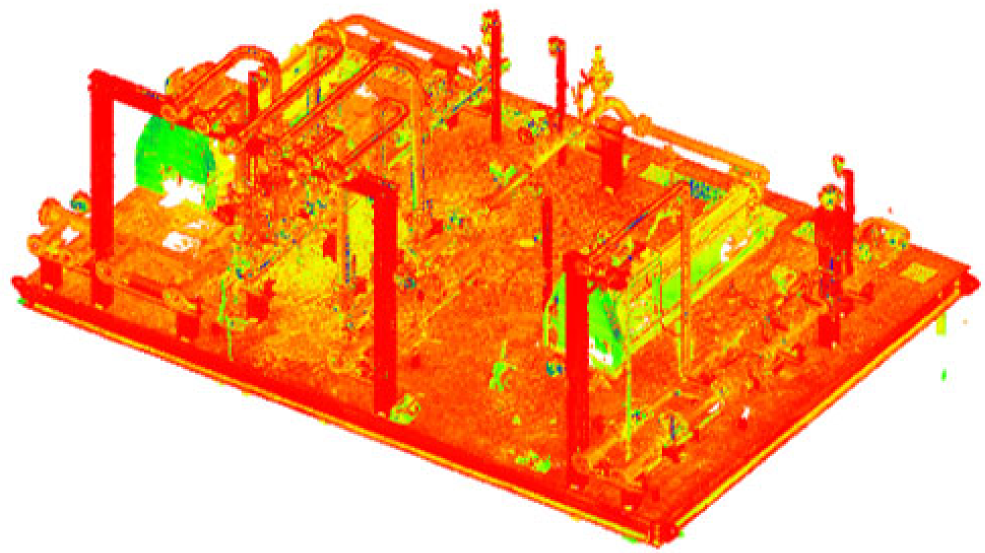


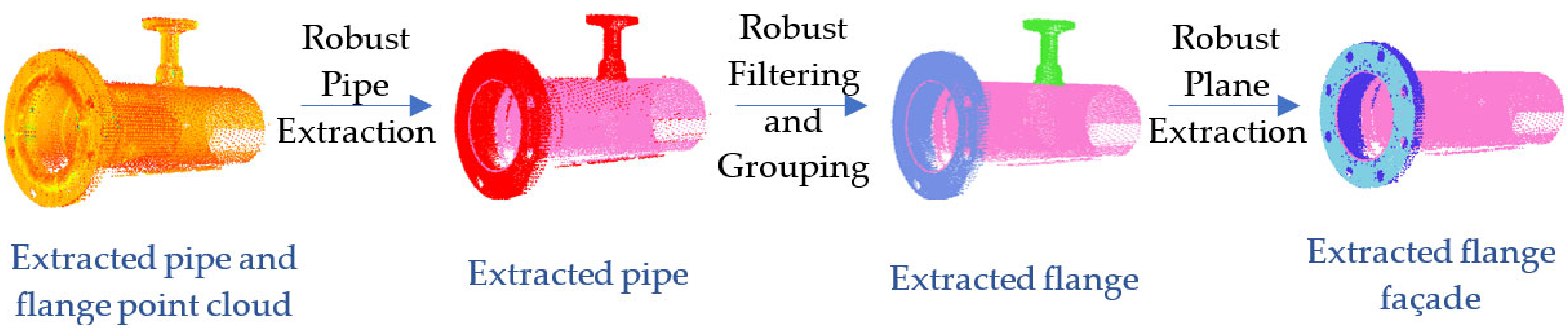
Maalek, R, DD Lichti, R Walker, A Bhavnani, J Y Ruwanpura (2019) Extraction of pipes and flanges from point clouds for automated verification of pre-fabricated modules in oil and gas refinery projects, Automation in Construction, 103, 150-167.

Dimensional Control

Pre-fabricated pipe and flange module



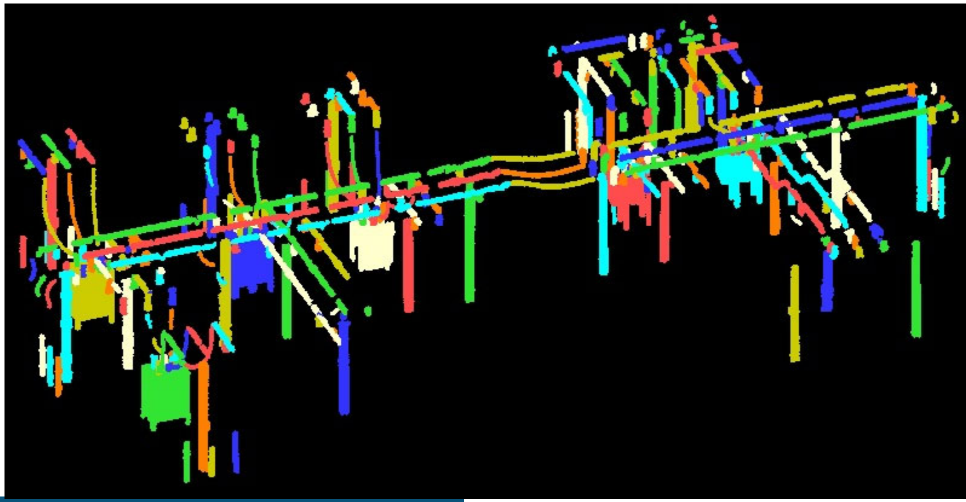




Arastounia, M and Lichti, DD (2015) Automated Recognition of Electrical Substation Components from LiDAR Data. Remote Sensing, 7, 15605-15629.

As-Built Modelling

Electrical substation



Hadavandsiri, Z, Lichti, DD, Jahraus, A and Jarron D (2019) Concrete Damage Classification of Terrestrial Laser Scanning Point Clouds through Systematic Threshold Definition. ISPRS International Journal of Geoinformation. 8 (12), 0585.

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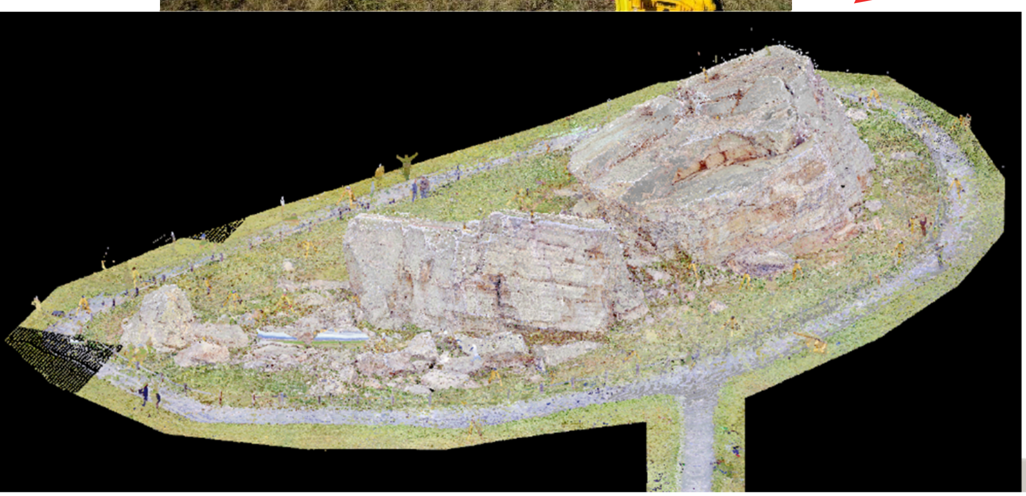
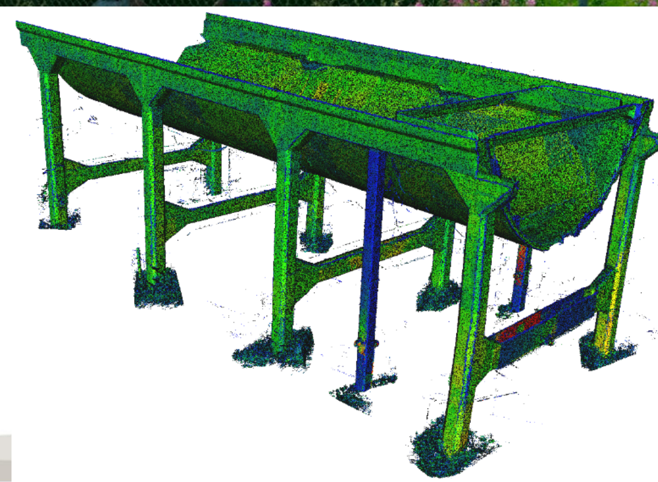
Digital Heritage Recording

Historic aqueduct





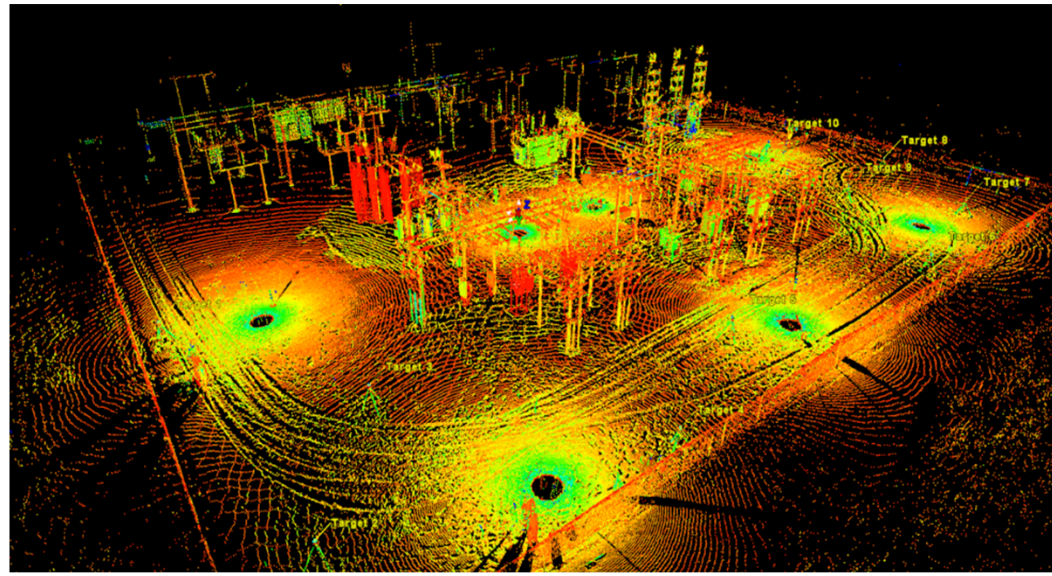
TLS Network Design

- An important QA process
- Given
  - A measurement volume
  - Design criteria (e.g. precision)

determine the

  - Datum definition
  - Configuration of viewpoints (VP planning) and targets
  - Observation weights
  - Densification measures

for complete site coverage



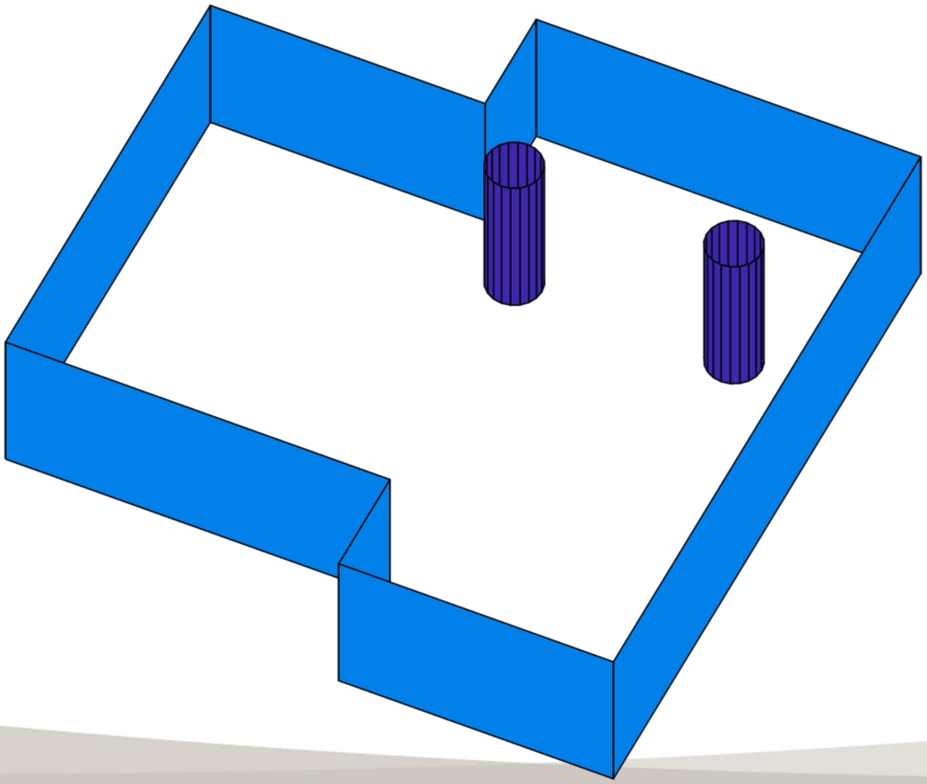
TLS Network Design (cont'd)

Outline

1. Overview of VP planning
2. Object precision modelling to support VP planning

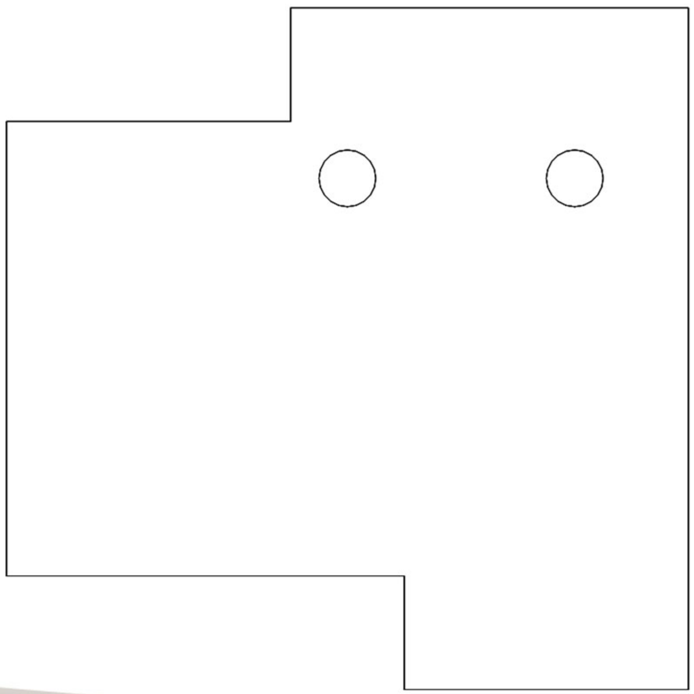
VP Planning

- Existence of a prior model is usually assumed



VP Planning (cont'd)

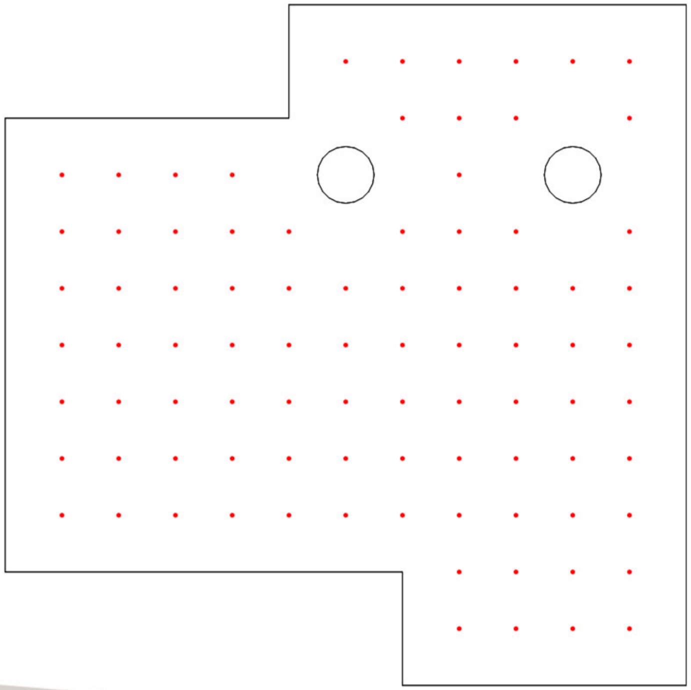
- Analyses are usually performed in 2D (plan view)



Where to put the instrument?

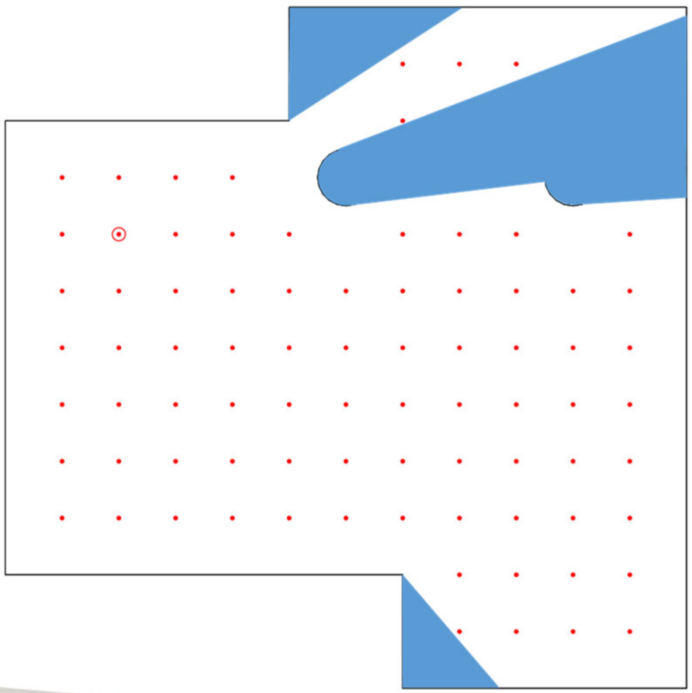
VP Planning (cont'd)

- The measurement volume is discretized—candidate VPs



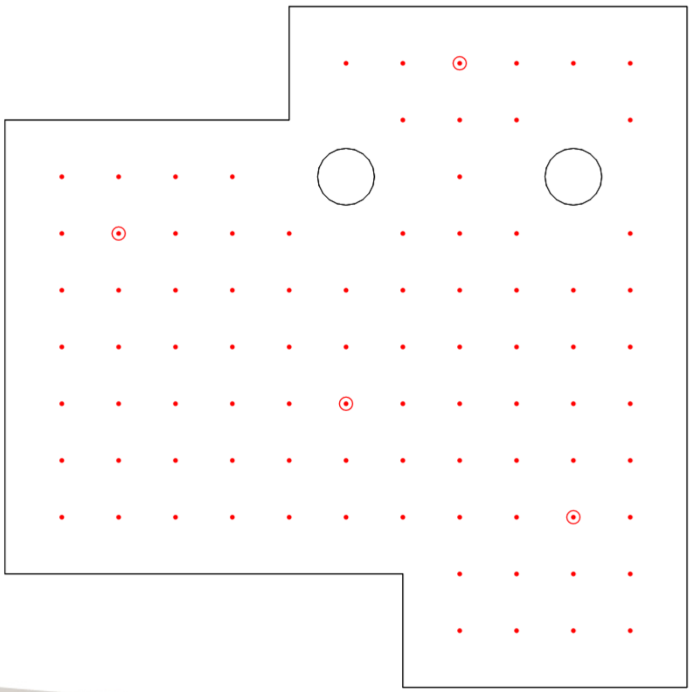
VP Planning (cont'd)

- Visibility and quality analyses are conducted for each candidate VP



VP Planning (cont'd)

- The smallest set of VPs needed to achieve complete site coverage within specified quality criteria is identified



Greedy methods are most commonly used

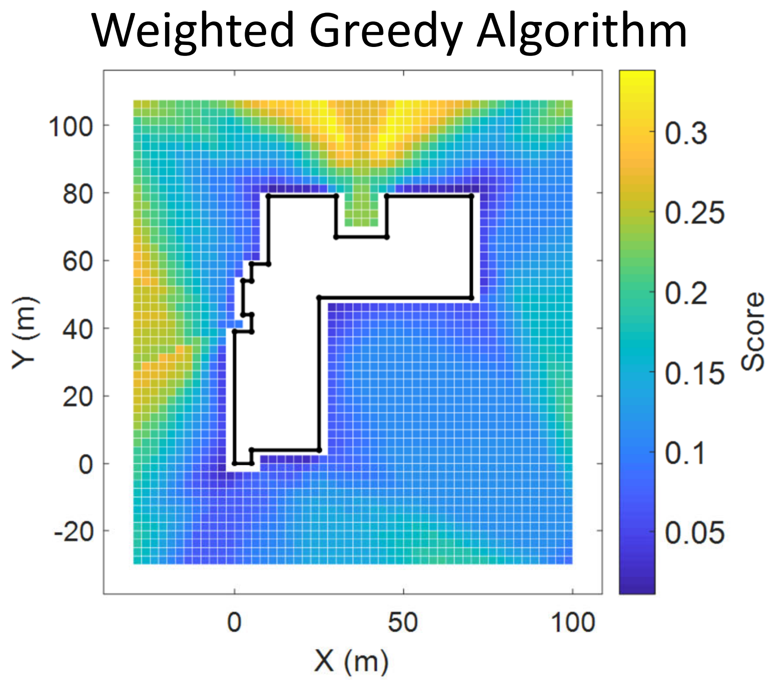
Data Quality Criteria

- Design measures
  - Completeness
  - Precision: point confidence regions (level of accuracy)
  - Reliability: robustness of the network
  - Resolution: information content (level of detail)
  - Overlap (“registrability”)
- Simplified design measures are often used to reduce the number of computations
  - Minimum and maximum range
  - Maximum incidence angle

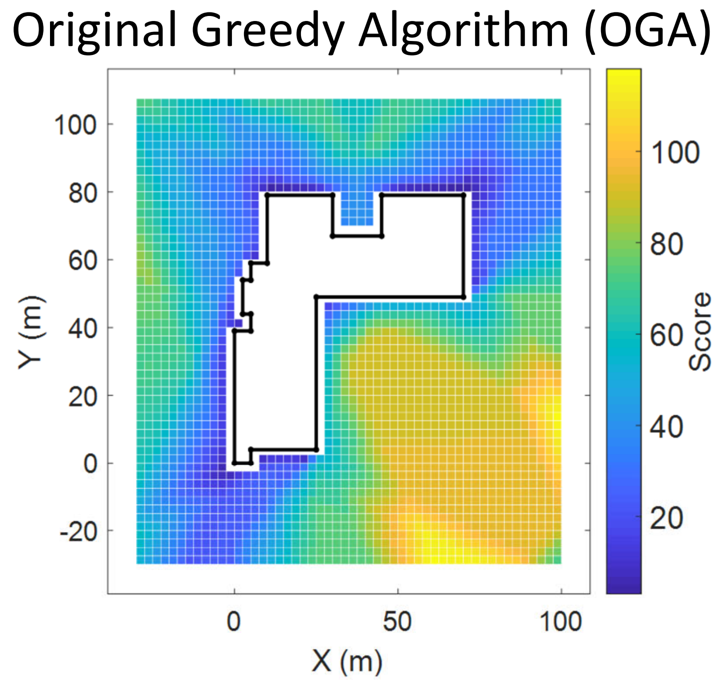
Greedy Algorithm Approaches

- Greedy algorithm
  - An object in the scene such as a wall is considered visible from a candidate VP if the quality criteria are satisfied
  - The VP with the most visible objects is added to the network
- Weighted greedy algorithm (WGA)
  - Higher priority is given to a VP from which objects are visible from few locations (difficult coverage)
  - Lower priority is given to a VP covering objects that are visible from many locations (easy coverage)
- Hierarchical WGA
  - VP planning performed at multiple resolutions to reduce the number of computations

WGA



a. Weighted scores



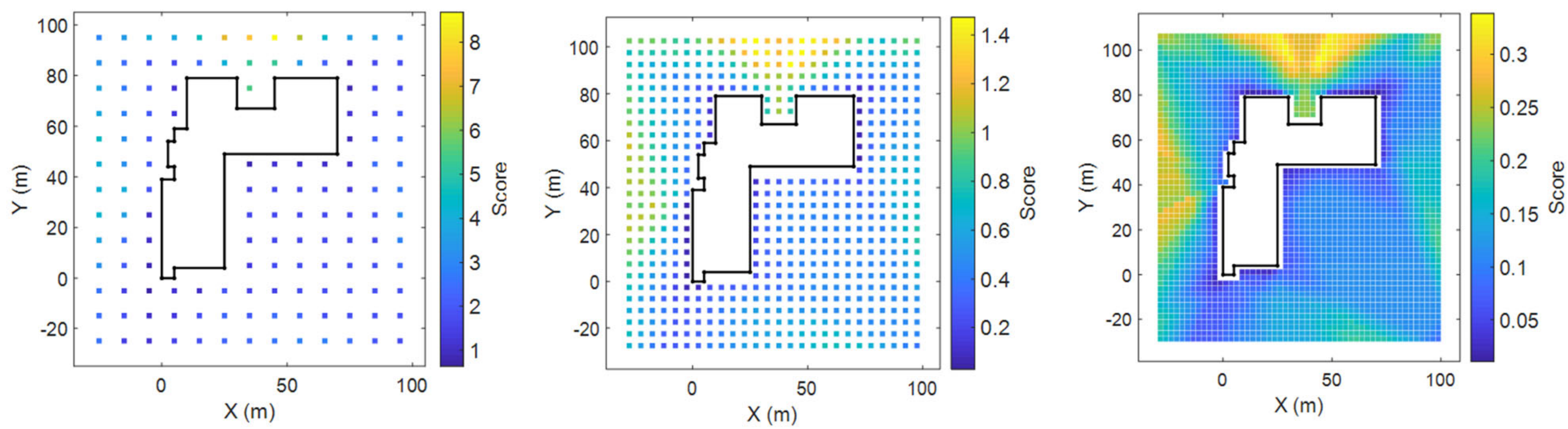
b. Binary scores

Heat maps for VP candidates with $\sigma = 2.5\ \mathrm{m}$, σ: step length

Jia, F and DD Lichti (2019) A Model-Based Design System for Terrestrial Laser Scanning Networks in Complex Sites. Remote Sensing, 11, 1749.

Hierarchical WGA

- **Assumption 1:** WGA solutions from different sampling resolutions exhibit similar geometry but have a different number of candidate VPs



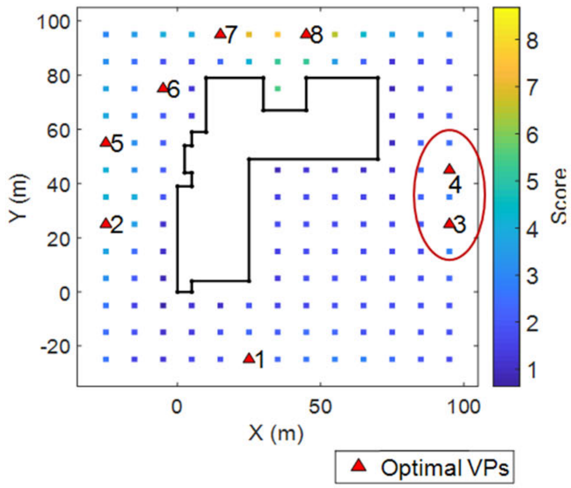
a. σ = 10 m   b. σ = 5 m   c. σ = 2.5 m

Heat maps with weighted scores under three resolutions

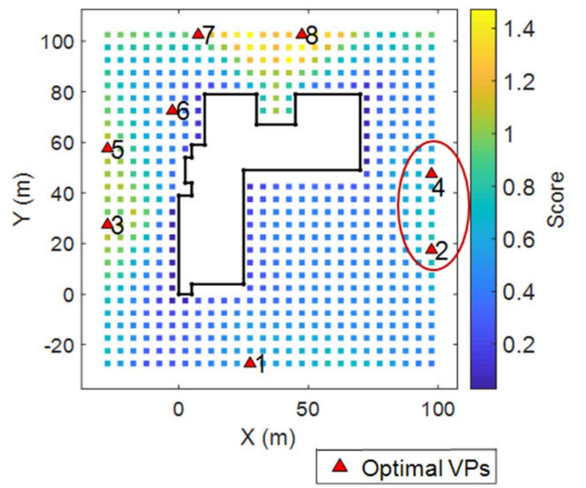
Jia, F and DD Lichti (2019) A Model-Based Design System for Terrestrial Laser Scanning Networks in Complex Sites. Remote Sensing, 11, 1749.

Hierarchical WGA (cont'd)

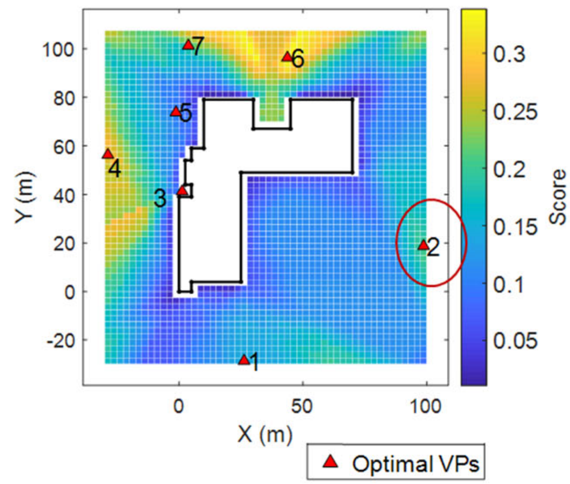
- **Assumption 2:** VPs can be hierarchically selected by starting at a global, coarse resolution and by increasing local resolution



a. σ = 10 m



b. σ = 5 m



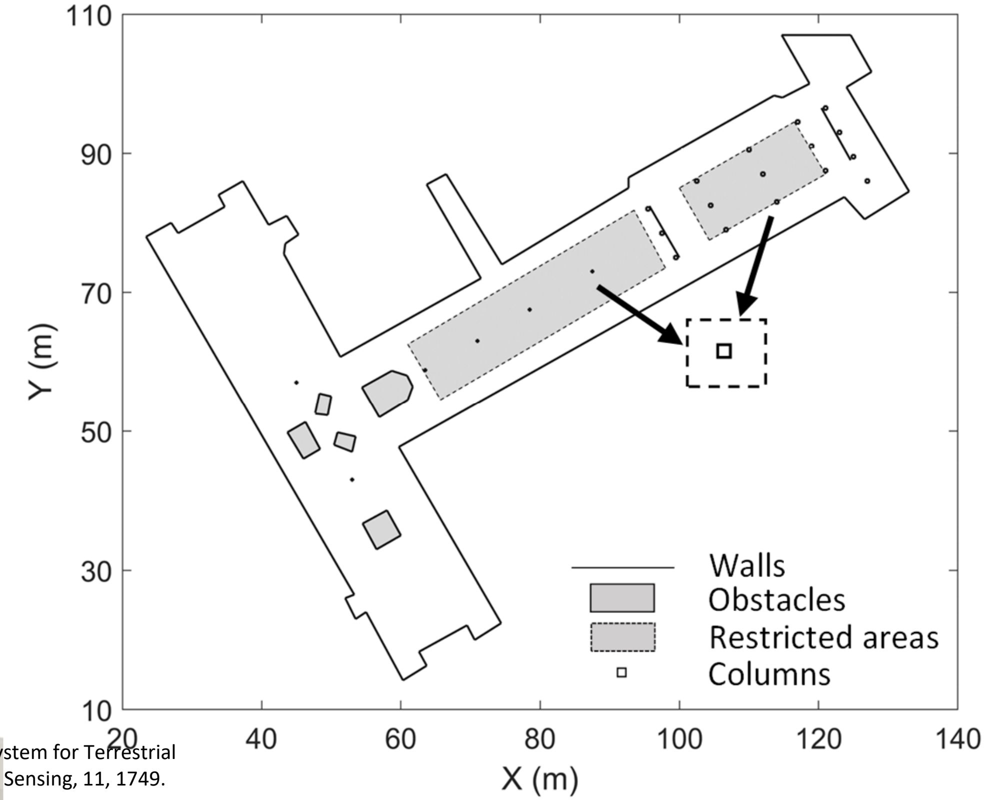
c. σ = 2.5 m

Solutions with WGA under three resolutions.

Jia, F and DD Lichti (2019) A Model-Based Design System for Terrestrial Laser Scanning Networks in Complex Sites. Remote Sensing, 11, 1749.

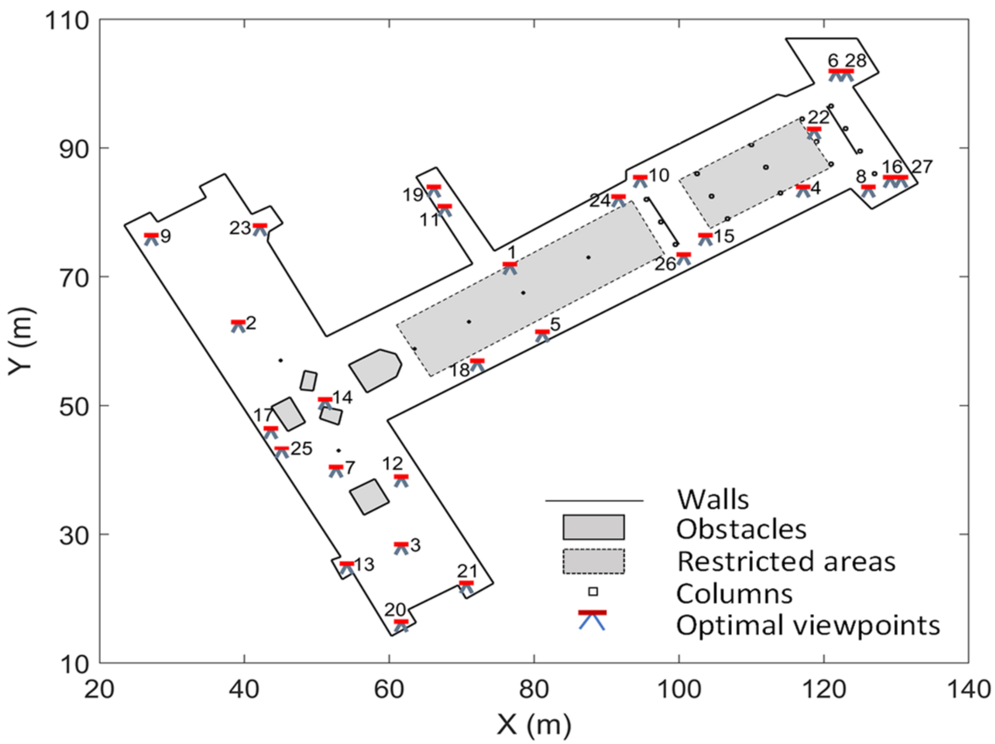
Application Example

- Multi-use indoor facility on the University of Calgary campus

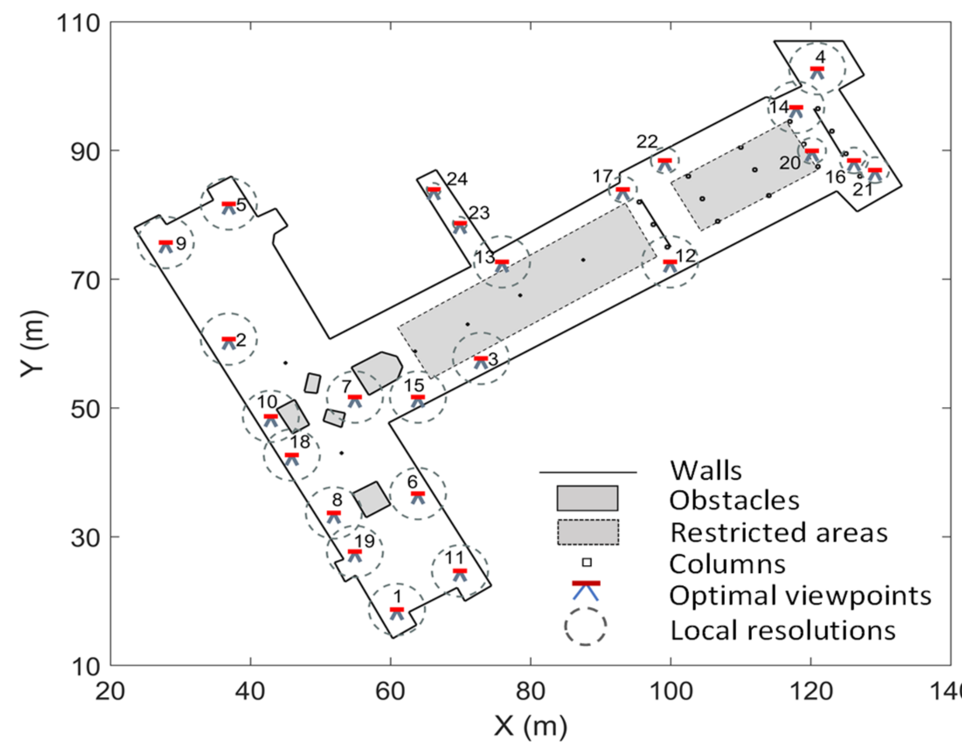


Jia, F and DD Lichti (2019) A Model-Based Design System for Terrestrial Laser Scanning Networks in Complex Sites. Remote Sensing, 11, 1749.

Example (cont'd)



Non-hierarchical + OGA: 28 VPs
1.3 h runtime

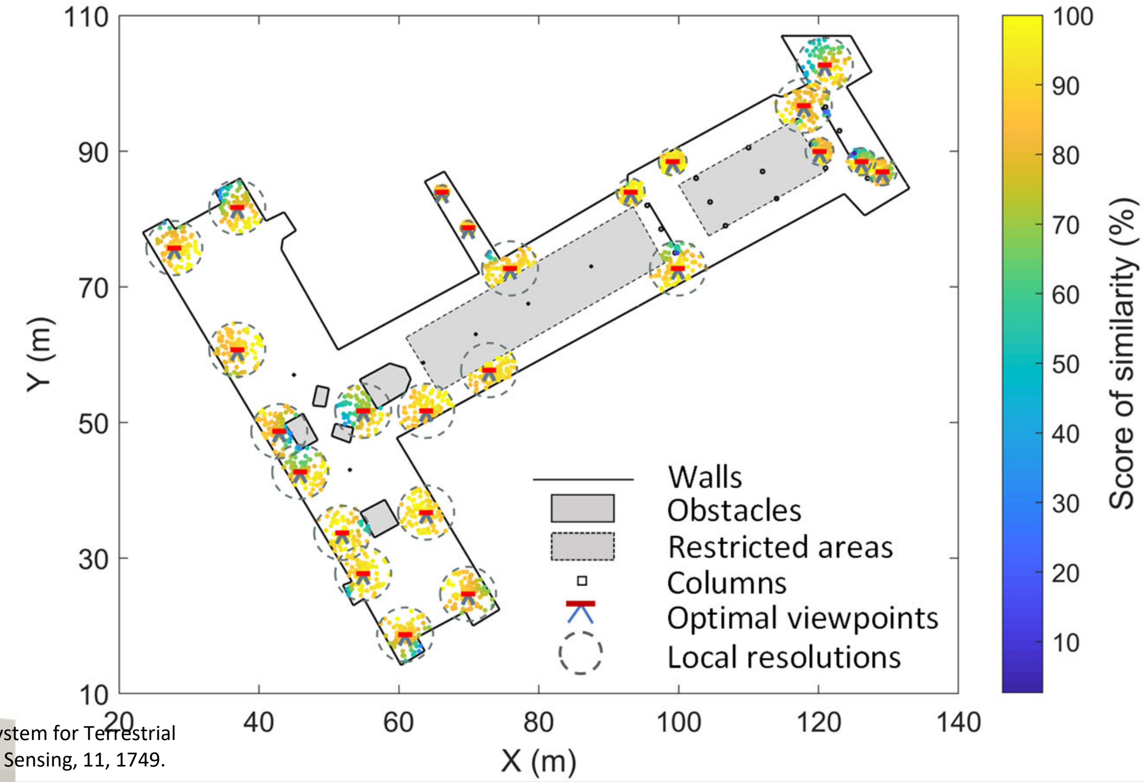


Hierarchical + WGA: 24 VPs
0.25 h runtime

Jia, F and DD Lichti (2019) A Model-Based Design System for Terrestrial Laser Scanning Networks in Complex Sites. Remote Sensing, 11, 1749.

Example (cont'd)

100 random VPs generated within local resolution
Colour scale indicates % of visible segments that are visible from random location



Jia, F and DD Lichti (2019) A Model-Based Design System for Terrestrial Laser Scanning Networks in Complex Sites. Remote Sensing, 11, 1749.

Some Open Problems

- 3D analysis is not generally performed
- Zenith/elevation angle is excluded as a design measure
- Rigorous quantification of point cloud density is missing
- Data quality criteria are simplified <u>point</u> precision measures as a function of range and incidence angle
- Object (plane/line or cylinder/circle) precision is more relevant but is <u>not</u> analyzed
- Others…

Factors Affecting Object Precision

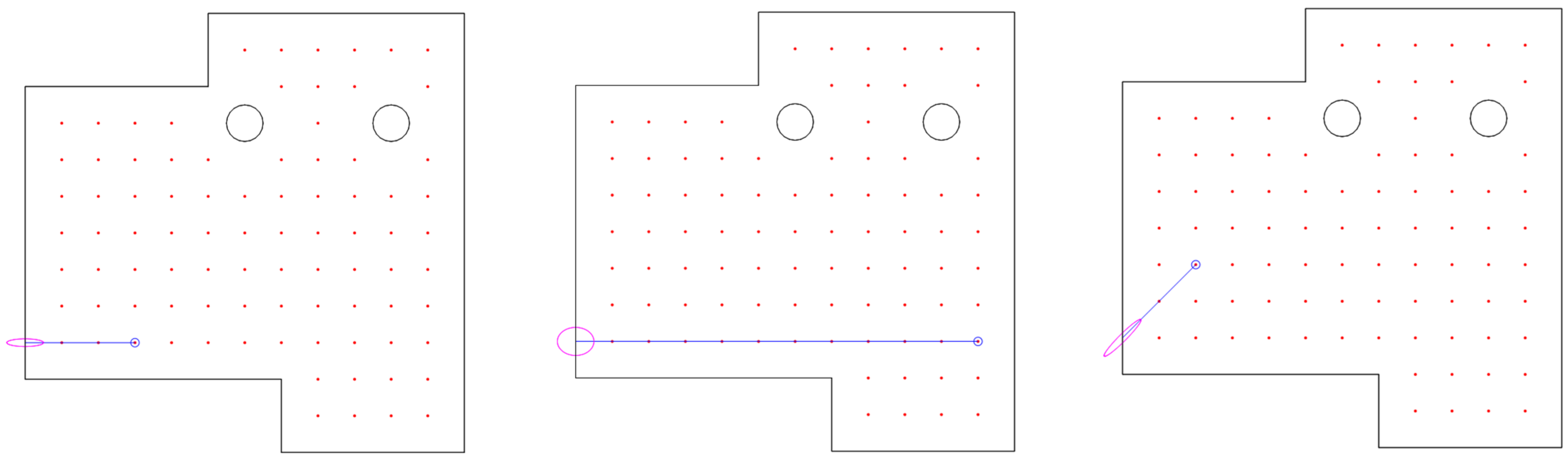
1. Observation precision: a function of instrumentation and environment
2. VP registration: a function of target geometry, target coordinate precision and observation precision
3. Distribution of the observations on the object: a function of instrumentation and network geometry

Factors Affecting Object Precision (cont'd)

1. Observation precision

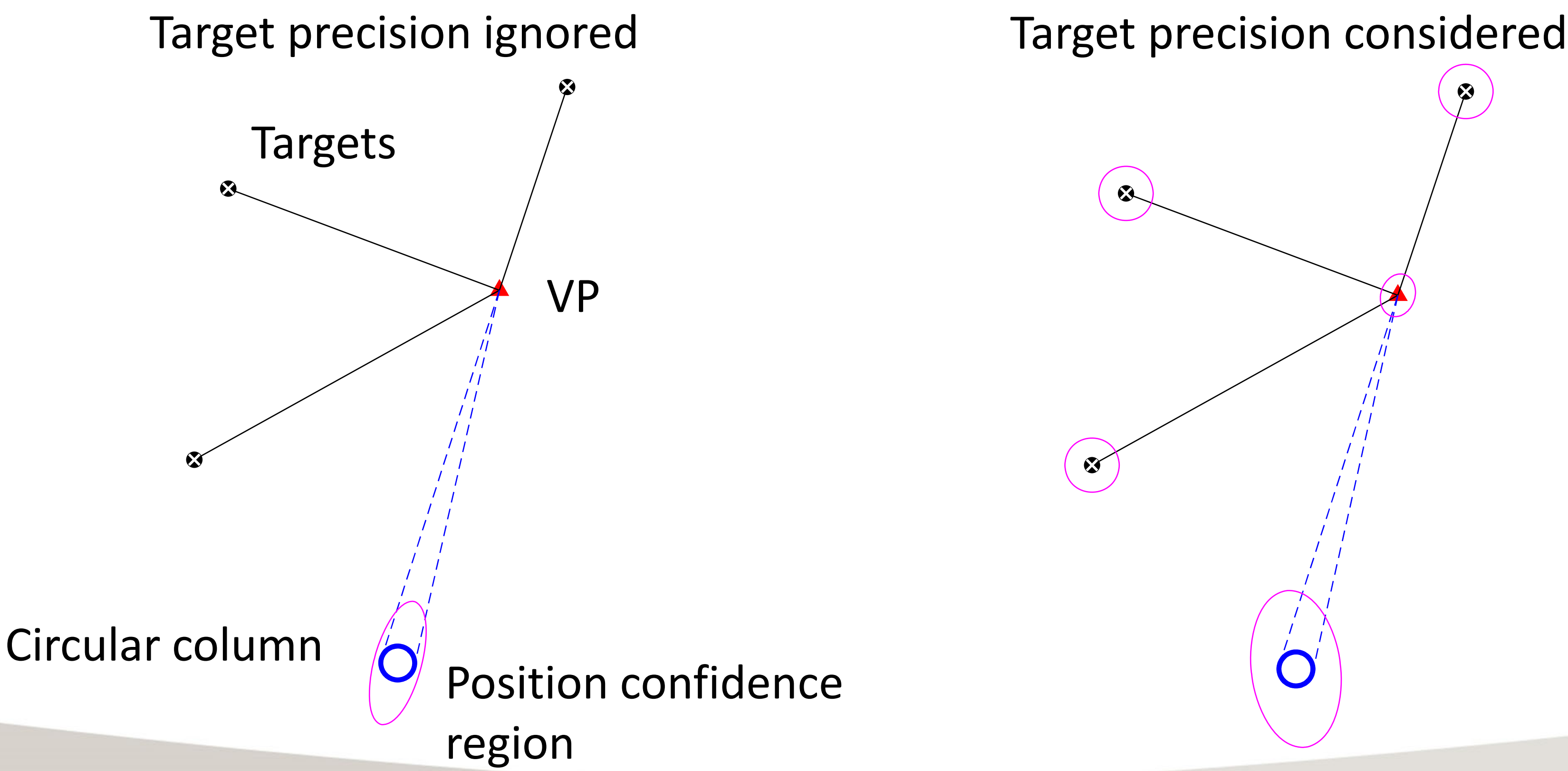
Range

Incidence angle



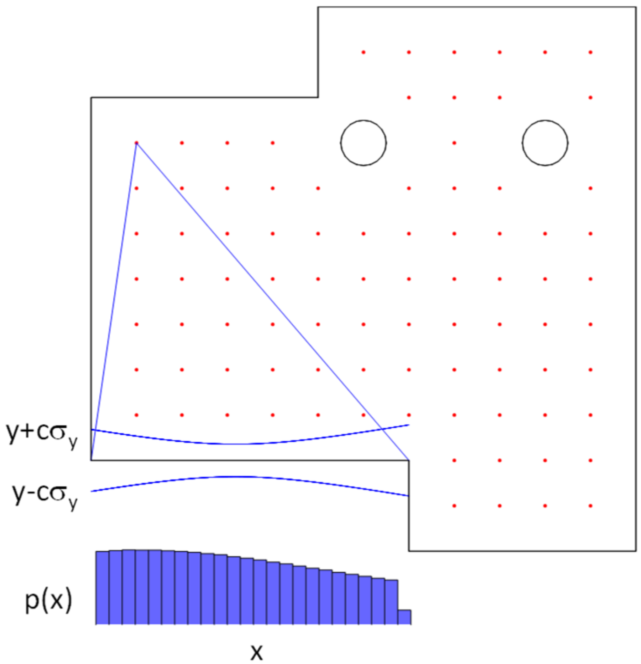
Factors Affecting Object Precision (cont'd)

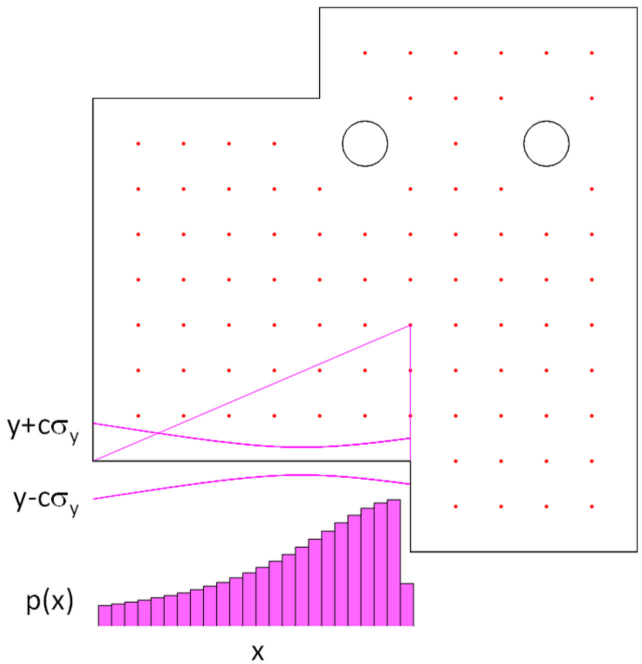
2. VP registration



Factors Affecting Object Precision (cont’d)

3. The distribution of the observations

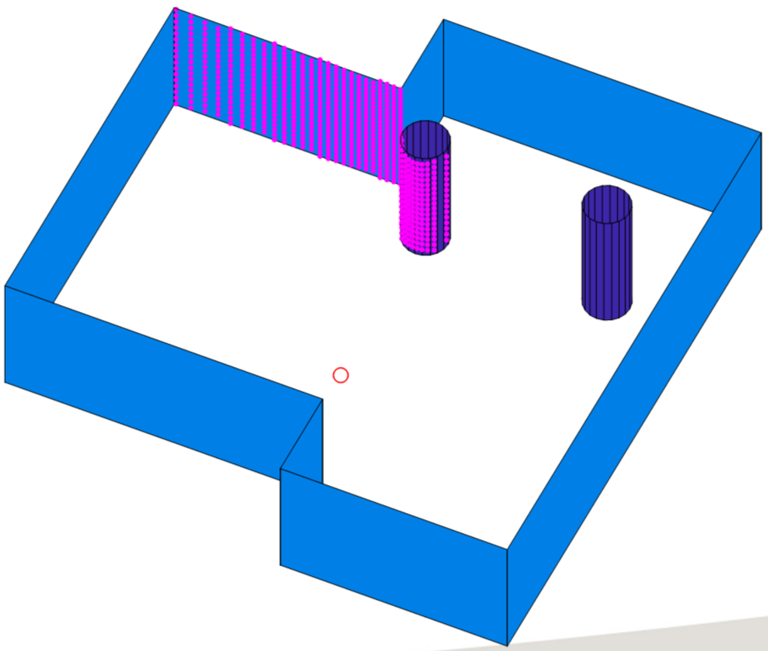




Modelling the Distribution of Observations

How can the observation distribution be rigorously accounted for at the design stage?

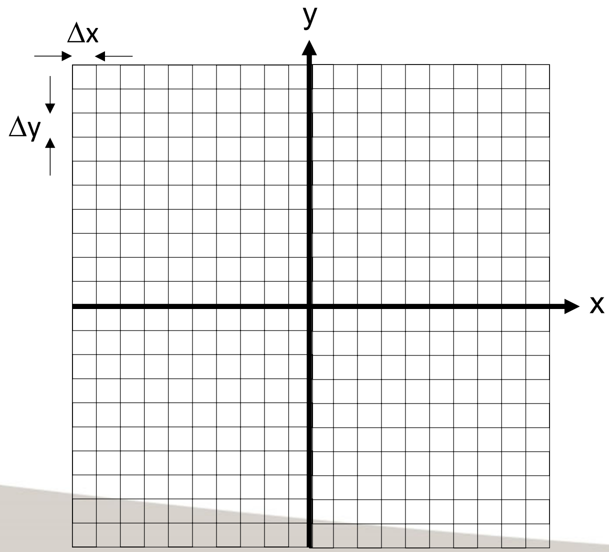
1. Simulation of discrete observations (artificial point cloud)
    - Generate artificial observations from each VP by ray casting
    - Form and invert the normal equations matrix to obtain the object parameter covariance matrix

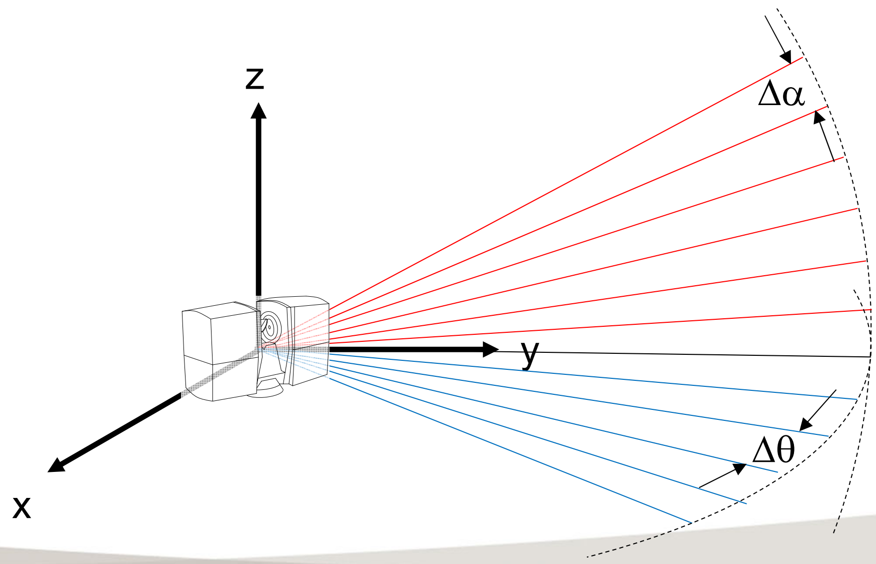


Discrete Simulation Approach (cont'd)

- TLS sampling model
  - A TLS collects spherical coordinates of a scene: range (ρ) as a function of horizontal (θ) and vertical (α) deflection angles
  - It can be modelled as a uniform sampling device like a camera

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \rho \sin\theta \cos\alpha \\ \rho \cos\theta \cos\alpha \\ \rho \sin\alpha \end{pmatrix}$$



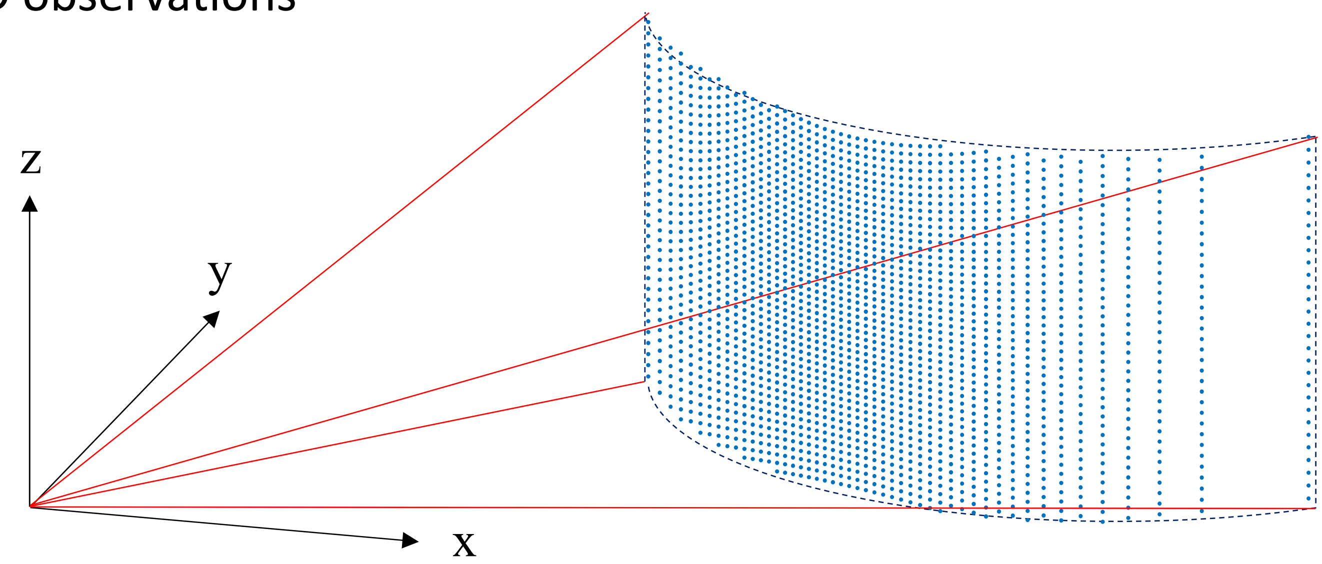


Discrete Simulation Approach (cont'd)

- Object model (cylinder example)
  - Project rays from a VP onto the object
  - Result: discrete set of 3D observations

$$u^2 + v^2 - r^2 = 0$$

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \mathbf{R}_2(\phi)\mathbf{R}_1(\omega)\begin{pmatrix} x - x_c \\ y - y_c \\ z \end{pmatrix}$$



Discrete Simulation Approach (cont'd)

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- Weight matrix of observations

$$\mathbf{P} = \mathbf{C}^{-1} = \mathrm{diag}\left(\frac{1}{\sigma^2_{\rho_1}} \quad \frac{1}{\sigma^2_{\theta_1}} \quad \frac{1}{\sigma^2_{\alpha_1}} \quad \frac{1}{\sigma^2_{\rho_2}} \quad \frac{1}{\sigma^2_{\theta_2}} \quad \frac{1}{\sigma^2_{\alpha_2}} \quad \cdots \right)$$

- Linearized functional model of the object (cylinder)

$$\mathbf{A}\hat{\boldsymbol{\delta}} + \mathbf{B}\hat{\mathbf{v}} + \mathbf{w} = \mathbf{0}$$

- Least-squares normal equations

$$\mathbf{A}^{\mathrm{T}}\left(\mathbf{B}\mathbf{P}^{-1}\mathbf{B}^{\mathrm{T}}\right)^{-1}\mathbf{A}\hat{\boldsymbol{\delta}} = -\mathbf{A}^{\mathrm{T}}\left(\mathbf{B}\mathbf{P}^{-1}\mathbf{B}^{\mathrm{T}}\right)^{-1}\mathbf{w}$$

$$\mathbf{N}\hat{\boldsymbol{\delta}} = -\mathbf{u}$$

Discrete Simulation Approach (cont'd)

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- Covariance matrix of object (cylinder) parameters

$$\underset{5,5}{\mathbf{C}_{\hat{\mathbf{x}}}} = \mathbf{N}^{-1} = \left(\mathbf{A}^{\mathrm{T}}\left(\mathbf{B}\mathbf{P}^{-1}\mathbf{B}^{\mathrm{T}}\right)^{-1}\mathbf{A}\right)^{-1}$$

$$= \begin{pmatrix} \sigma_{x_c}^2 & \sigma_{x_c y_c} & \sigma_{x_c \omega} & \sigma_{x_c \phi} & \sigma_{x_c r} \\ & \sigma_{y_c}^2 & \sigma_{y_c \omega} & \sigma_{y_c \phi} & \sigma_{y_c r} \\ & & \sigma_{\omega}^2 & \sigma_{\omega\phi} & \sigma_{\omega r} \\ & & & \sigma_{\phi}^2 & \sigma_{\phi r} \\ \mathrm{sym} & & & & \sigma_r^2 \end{pmatrix}$$

- The normal equations matrix $\mathbf{N}$ is comprised of double summations

New Approach

2. Compute the covariance matrix of parameters for the object in closed form without ray casting

- Define a new weight matrix

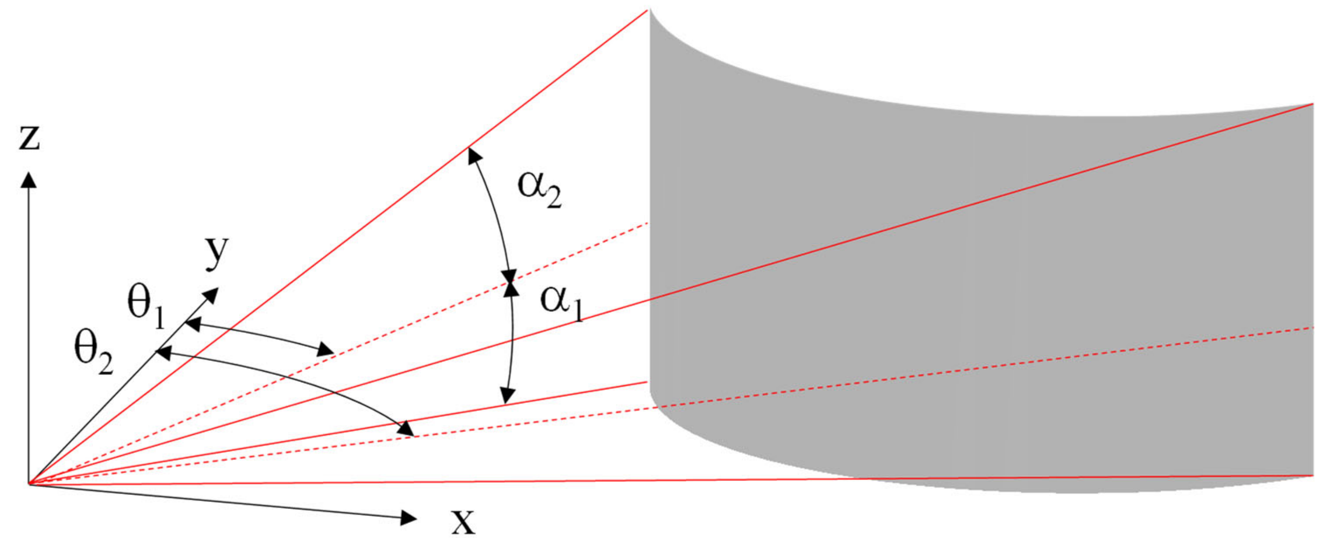
$$\mathbf{P} = \operatorname{diag}\begin{pmatrix} \dfrac{p(\theta_1, \alpha_1)}{\sigma^2_{\rho_1}} & \dfrac{p(\theta_1, \alpha_1)}{\sigma^2_{\theta_1}} & \dfrac{p(\theta_1, \alpha_1)}{\sigma^2_{\alpha_1}} & \cdots \end{pmatrix}$$

- The function $p(\theta,\alpha)$ describes the distribution of the observations and must satisfy the following conditions:

$$p(\theta,\alpha) > 0 \qquad \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(\theta,\alpha)\, d\theta\, d\alpha = 1$$

New Approach (cont'd)

- For the TLS sampling model, $p(\theta,\alpha)$ is uniform on the intervals defined by the scanning extents for the cylinder: (θ_1, θ_2) and (α_1, α_2)



New Approach (cont'd)

- Next, derive the range, ρ, as a function of the two angular variables, θ and α, for the cylinder model

$$\rho = g(\theta, \alpha)$$

and substitute it into the cylinder model

$$u^2 + v^2 - r^2 = 0$$

- Construct the normal equations and multiply them by $\Delta\theta\Delta\alpha$

$$\Delta\theta\Delta\alpha\mathbf{N}\hat{\boldsymbol{\delta}} = -\Delta\theta\Delta\alpha\mathbf{u}$$

where for m profiles and n samples per profile:

$$\Delta\theta = \frac{\theta_2 - \theta_1}{m} \quad \Delta\alpha = \frac{\alpha_2 - \alpha_1}{n}$$

New Approach (cont'd)

- Finally, the limit as $m,n \to \infty$ is taken: the double summations embedded in the normal equations matrix $\mathbf{N}$ become double integrals that are evaluated to determine object parameter precision
- Generation of many artificial observations by ray casting is not necessary
- Only the stochastic model and the basic geometry of the network design are needed to predict modelled object precision
  - Scanner locations (VPs)
  - Object (cylinder) parameters
- Even if numerical integration is required, the number of computations is greatly reduced

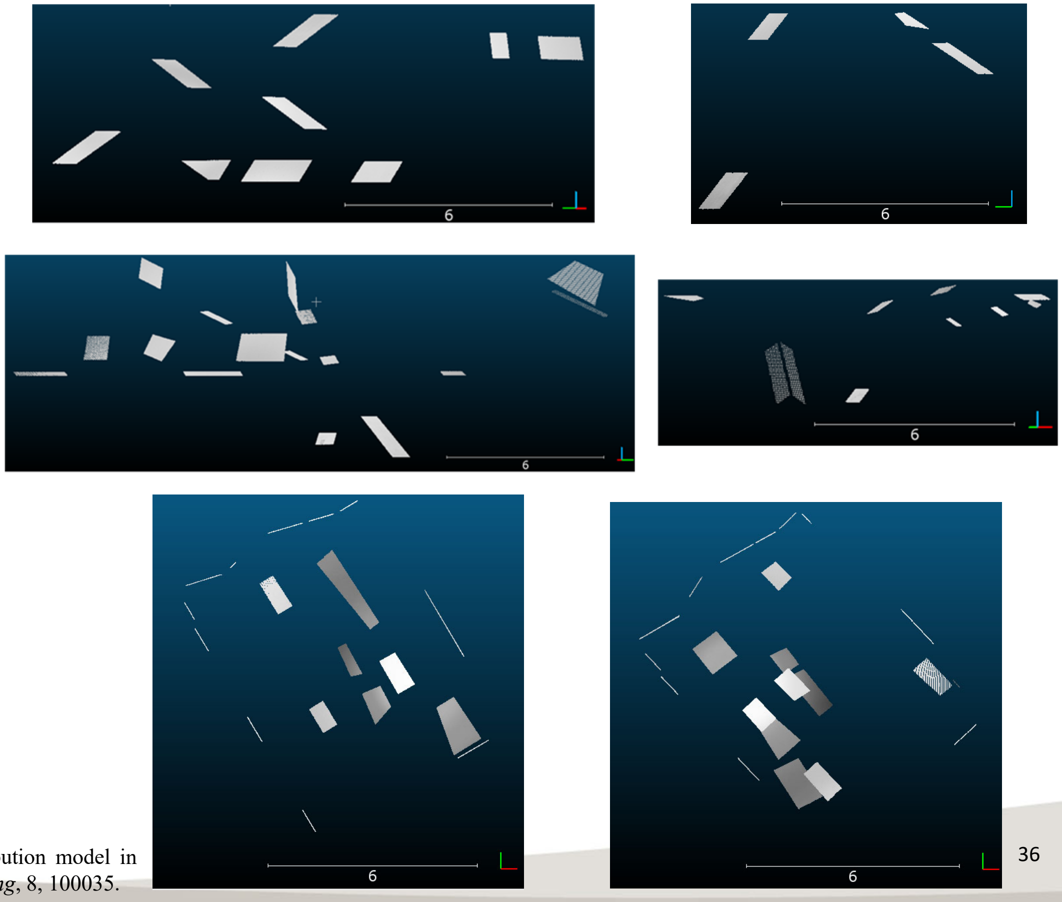
Testing

- 3D scanned objects
  - 90 scans of 6 vertical cylinders
  - 80 scanned vertical, horizontal and tilted planes
- Real data used for the reference to evaluate the new method in terms of
  - Standard deviation (precision), expressed as a % of “true” value determined from the discrete observations
  - Computational advantage, expressed as the ratio of CPU times for ray casting and the numerical integration

Testing (cont'd)

Cylinders

Planes

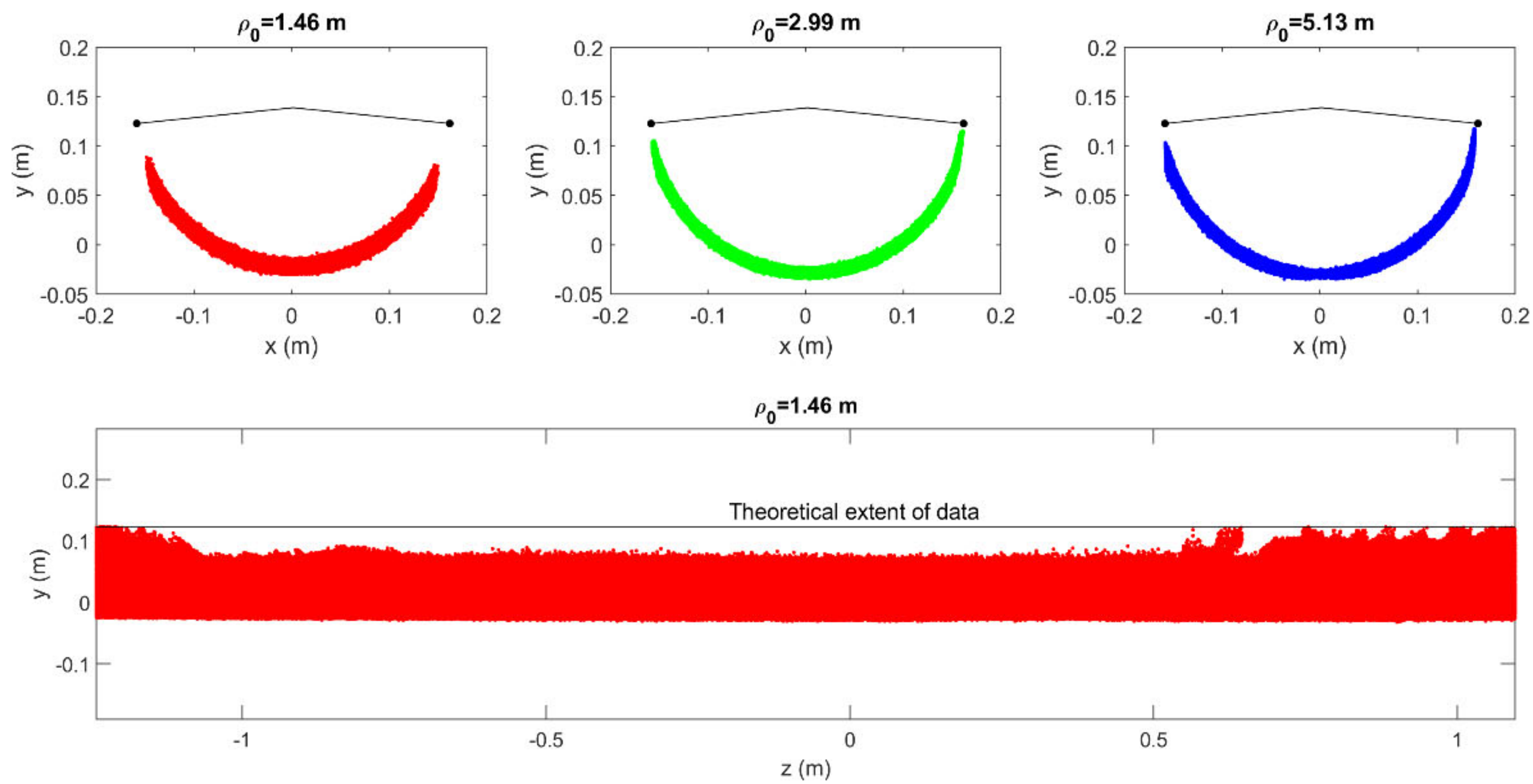


Lichti, DD, Chan, TO, Pexman, K (2023) Precision estimation of 3D objects using an observation distribution model in support of terrestrial laser scanner network design, *ISPRS Open Journal of Photogrammetry and Remote Sensing*, 8, 100035.

Cylinder Precision

	Difference	Mean % difference	Maximum |% difference|
Position	$\Delta\sigma_{xc}$	-3.3	20.4
	$\Delta\sigma_{yc}$	-5.3	26.3
Orientation	$\Delta\sigma_{\omega}$	0.3	3.9
	$\Delta\sigma_{\phi}$	-1.1	7.4
Radius	$\Delta\sigma_{r}$	-6.2	31.1

Cylinder Precision (cont'd)



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Plane Precision

Vertical Planes

	Difference	Mean % difference	Maximum |% difference|
Orientation	$\Delta\sigma_{\psi}$	0.9	3.8
	$\Delta\sigma_{\delta}$	0.4	0.7
Position	$\Delta\sigma_{d}$	0.8	3.8

Horizontal Planes

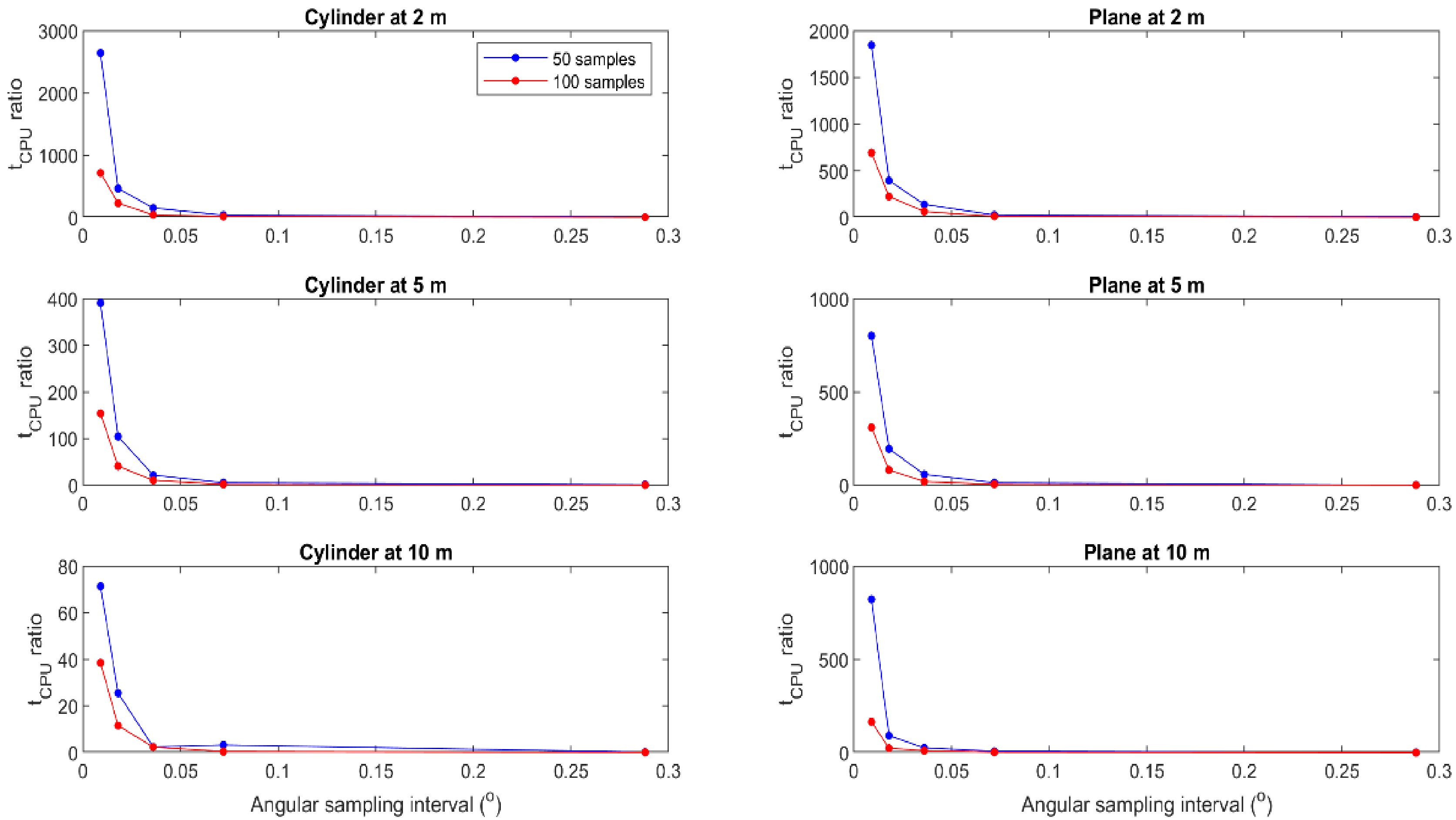
	Difference	Mean % difference	Maximum |% difference|
Orientation	$\Delta\sigma_{a}$	0.3	0.8
	$\Delta\sigma_{b}$	0.4	0.7
Position	$\Delta\sigma_{d}$	0.4	0.8

Tilted Planes

	Difference	Mean % difference	Maximum |% difference|
Orientation	$\Delta\sigma_{\psi}$	0.6	2.8
	$\Delta\sigma_{\delta}$	0.8	3.6
Position	$\Delta\sigma_{d}$	0.6	4.3

Lichti, DD, Chan, TO, Pexman, K (2023) Precision estimation of 3D objects using an observation distribution model in support of terrestrial laser scanner network design, *ISPRS Open Journal of Photogrammetry and Remote Sensing*, 8, 100035.

Computational Advantage



Conclusions

- VP planning is an important QA process for scanning complex environments
- Object precision should be used as the quality criterion instead of point precision
- The computations for this more rigorous planning may be performed by simulation: ray casting
- Or, the new approach using integrals can be used to eliminate the need for ray casting
- The accuracy of standard deviation estimates is high
- Computational efficiency is high

Acknowledgements

- Dr Mozhdeh Shahbazi
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- Prof Peter Dawson
- Natural Sciences and Engineering Research Council
- Canada Foundation for Innovation
- Alberta Innovates
- China Scholarship Council

2026 ISPRS Congress

isprs 2026 TORONTO

- Toronto, Canada
- Date: 4-11 July 2026
- Venue: Metro Toronto Convention Centre

  https://www.isprs2026toronto.com
- More details to come!


Thank you.
Questions?