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Piketimi dhe kontrolli gjeodezik i ndërtimit dhe monitorimi i deformimeve dhe stabilitetit të objekteve

Bashkim IDRIZI

Training objectives

✓ Understand geodetic stakeout and construction control procedures
✓ Explain accuracy requirements and design principles for engineering geodetic networks
✓ Present methodologies for deformation analysis and stability assessment
✓ Introduce monitoring systems for engineering structures and infrastructure
✓ Compare classical and modern monitoring approaches including GNSS, total stations and InSAR
✓ Demonstrate practical applications through real engineering case studies
✓ Support reliable engineering decision-making through accurate geodetic monitoring

"Reliable geodetic monitoring is essential for safe, accurate and sustainable infrastructure."

Agenda – Contents

A Priori Accuracy and Network Design
•A priori accuracy analysis
•Engineering geodetic network design
•Observation planning and optimization

Construction Stakeout, Control and Quality Assessment
•Horizontal and vertical stakeout methods
•Error ellipses and tolerance assessment
•Accuracy verification and quality control

Deformation Analysis and Monitoring
•Mathematical models for deformation analysis
•Classical and modern monitoring approaches
•Monitoring systems for engineering structures

Practical Applications
•Engineering structures and infrastructure
•Dams and deformation monitoring
•Selected real engineering case studies

"From mathematical network design to engineering monitoring and decision support."

A priori accuracy for engineering geodetic networks

- A priori analysis of a geodetic network is the mathematical process of isolating and evaluating network quality *before any field observations are made*. It relies on a critical principle of Least Squares estimation: **the precision of adjusted coordinates depends entirely on network geometry and observation weights, not on the actual field measurement values**.
- In structural engineering and construction stakeout, we must prove mathematically that our planned network can isolate true structural deformation or position structural elements within design tolerances. If the pre-analysis reveals that our measurement layout cannot meet these thresholds, the network configuration must be redesigned.
- Contents: 1. Identify Structure Class
  2. Define Instrument Error Budgets
  3. Build the Stochastic Model
  4. Optimize Station Geometry

1. Identify Structure Class

Classify the project to find its tolerance tier.

- Tier 1: High-precision manufacturing and industrial machinery.
- Tier 2: Bridges, high-rise buildings, and tunnels.
- Tier 3: General earthworks, roads, and utilities.

2. Define Instrument Error Budgets

Quantify the sensory limits of field hardware.

- Total station angular limits ($\sigma_\alpha = \pm 0.5''$ to $\pm 5''$).
- Total station distance limits ($\sigma_d = \pm 1$ mm ± 1 ppm).
- GNSS RTK vector limits ($\sigma_{RTK} = \pm 8$ mm ± 1 ppm).
- Digital leveling limits ($\sigma_z = \pm 0.3$ mm/km).

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3. Build the Stochastic Model

Compute the theoretical error propagation matrix.
The geometric strength of the network is simulated using the design matrix $\mathbf{A}$ and the observation weight matrix $\mathbf{P}$ to output the a priori variance-covariance matrix $\mathbf{C}_x$:

$$\mathbf{C}_x = \sigma_0^2(\mathbf{A}^T\mathbf{P}\mathbf{A})^{-1}$$

Where:

- σ_0^2 is the a priori reference variance.
- $\mathbf{A}$ contains partial derivatives of the network geometry configuration.
- $\mathbf{P}$ is the weight matrix derived from instrument error budgets.

4. Optimize Station Geometry

Adjust network layout until ellipses fall within limits.

- Extract point coordinate standard deviations $(\sigma_x, \sigma_y, \sigma_z)$.
- Calculate the dimensions of the error ellipses.
- Add stations or lines of sight if ellipses exceed structural limits.

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General Construction Accuracy Requirements Matrix

Construction Project Type	Relative Precision Range	Absolute Positional Accuracy ($\sigma_{x,y}$)	Vertical Accuracy (σ_z)	Typical Instrument Mix
Industrial / Particle Accelerators	$> 1:500,000$	± 0.5 mm to ± 1.5 mm	± 0.2 mm	Laser Trackers, Sub-second Total Stations
High-Rise Buildings & Tunnels	$1:100,000 - 1:200,000$	± 2 mm to ± 5 mm	± 1 mm to ± 2 mm	1" Total Stations, Precise Digital Levels
Standard Commercial Buildings	$1:20,000 - 1:50,000$	± 5 mm to ± 10 mm	± 5 mm	3" Total Stations, GNSS Network RTK
Earthworks, Roads, & Utilities	$1:10,000 - 1:20,000$	± 15 mm to ± 25 mm	± 20 mm	GNSS RTK, Machine Control Sensors

The Three Orders of Network Design

Geodetic optimization is categorized into distinct design phases:

- **Zero-Order Design (ZOD):** Solving for the optimal reference system (datum definition).
- **First-Order Design (FOD):** Solving for the optimal geometric configuration (where to place stations and targets).
- **Second-Order Design (SOD):** Solving for the optimal distribution of observation weights (choosing instruments and observation counts).

Comprehensive Mathematical Framework

The entire mathematical base of a priori analysis is rooted in the Gauss-Markov model of Least Squares estimation:

- The Functional Model (The Design Matrix A)
- Distance Observation Equation
- Horizontal Direction Equation
- The Stochastic Model (The Weight Matrix P)
- The Fundamental Error Propagation

The Functional Model (The Design Matrix $\mathbf{A}$)

The functional model relates the unknown coordinates to the theoretical observations through non-linear geometric equations (distances, horizontal angles, azimuths, zenith angles). Let $\mathbf{x}$ be the vector of coordinate corrections, and $\mathbf{l}$ be the vector of observations. The linearized system is expressed as:

$$\mathbf{v} = \mathbf{A}\mathbf{x} - \mathbf{l}$$

Where $\mathbf{A}$ is the **Design Matrix** containing the partial derivatives of the observation equations with respect to the unknown parameters (coordinates).

Distance Observation Equation

The spatial distance S_{ij} between station $i(X_i, Y_i, Z_i)$ and target $j(X_j, Y_j, Z_j)$ is:

$$S_{ij} = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2}$$

The corresponding row in the $\mathbf{A}$ matrix consists of the partial derivatives relative to the variables of interest:

$$\frac{\partial S_{ij}}{\partial X_i} = -\frac{X_j - X_i}{S_{ij}}, \quad \frac{\partial S_{ij}}{\partial X_j} = \frac{X_j - X_i}{S_{ij}}$$

Horizontal Direction Equation

The horizontal direction α_{ij} from station i to target j utilizes the horizontal distance $D_{ij} = \sqrt{(X_j - X_i)^2 + (Y_j - Y_i)^2}$:

$$\alpha_{ij} = \arctan\left(\frac{Y_j - Y_i}{X_j - X_i}\right) - \omega_i$$

Where ω_i is the unknown orientation uncorrected parameter of the total station instrument. The partial derivatives are:

$$\frac{\partial \alpha_{ij}}{\partial X_i} = \frac{Y_j - Y_i}{D_{ij}^2}, \quad \frac{\partial \alpha_{ij}}{\partial Y_i} = -\frac{X_j - X_i}{D_{ij}^2}, \quad \frac{\partial \alpha_{ij}}{\partial X_j} = -\frac{Y_j - Y_i}{D_{ij}^2}, \quad \frac{\partial \alpha_{ij}}{\partial Y_j} = \frac{X_j - X_i}{D_{ij}^2},$$

The Stochastic Model (The Weight Matrix $\mathbf{P}$)

The weight matrix $\mathbf{P}$ reflects the relative reliability and expected variances of different measurements. It is defined as the inverse of the a priori variance-covariance matrix of observations ($\mathbf{C}_l$):

$$\mathbf{P} = \sigma_0^2 \mathbf{C}_l^{-1}$$

Where σ_0^2 is the a priori reference variance (typically set to 1). If observations are assumed to be statistically independent, $\mathbf{C}_l$ is a diagonal matrix, and the weights are simply:

$$P_i = \frac{\sigma_0^2}{\sigma_i^2}$$

The Fundamental Error Propagation

Applying the law of error propagation to the Least Squares normal equations yields the **A Priori Variance-Covariance Matrix of Parameters ($\mathbf{C}_x$)**:

$$\mathbf{C}_x = \sigma_0^2(\mathbf{A}^T\mathbf{P}\mathbf{A})^{-1} = \sigma_0^2\mathbf{N}^{-1}$$

Where $\mathbf{N} = \mathbf{A}^T\mathbf{P}\mathbf{A}$ is the matrix of normal equations. Notice that $\mathbf{C}_x$ **depends solely on the geometry ($\mathbf{A}$) and instrument precisions ($\mathbf{P}$)**. No field measurements are required to evaluate it.

3. Rigorous Multi-Sensor Weight Matrix Formulation ($\mathbf{P}$)

When combining heterogeneous sensors—such as Terrestrial Total Stations (Angles/Distances) and GNSS (Baseline Vectors)—the observation variance-covariance matrix $\mathbf{C}_l$ must be structured as a block-diagonal matrix to account for differing physical behaviors and stochastic correlations.

$$\mathbf{C}_l = \begin{bmatrix} \mathbf{C}_{\text{TotalStation}} & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_{\text{GNSS}} \end{bmatrix}$$

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Total Station Sub-Matrix ($\mathbf{C}_{\text{TotalStation}}$)

For an independent setup, this block is diagonal. The variances must account for instrument specifications, targeting errors, and centering errors.

$$\sigma_{\text{total}}^2 = \sigma_{\text{reading}}^2 + \sigma_{\text{centering}}^2 + \sigma_{\text{targeting}}^2$$

1. **Distance Measurements (S):** Instrument specs are typically given as $a\,\text{mm} + b\,\text{ppm}$.

$$\sigma_S = \pm\sqrt{a^2 + \left(b \cdot 10^{-6} \cdot S\right)^2}$$

2. **Direction Measurements (α):** Angles degrade over short distances due to centering limits.

$$\sigma_\alpha^2 = \sigma_{\text{inst}}^2 + \frac{\sigma_{\text{center, inst}}^2 + \sigma_{\text{center, target}}^2}{D^2} \cdot \rho^2$$

Where $\rho = 206264.8''/\text{radian}$.

GNSS Baseline Sub-Matrix ($\mathbf{C}_{\text{GNSS}}$)

GNSS observations are entered into geodetic networks as 3D baseline vectors ($\Delta X, \Delta Y, \Delta Z$) between points. These components are highly correlated due to atmospheric conditions and satellite geometry. For every baseline k, a fully populated 3×3 covariance block must be inserted:

$$\mathbf{C}_{\text{GNSS},k} = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{YX} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{ZX} & \sigma_{ZY} & \sigma_Z^2 \end{bmatrix}$$

These components are extracted directly from the GNSS baseline processing software engine based on carrier-phase ambiguities and carrier-to-noise ratios.

Building the Global Weight Matrix

To calculate the overall weight matrix, invert each block independently and assemble them:

$$\mathbf{P} = \sigma_0^2 \begin{bmatrix} \mathbf{C}_{\text{TotalStation}}^{-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_{\text{GNSS}}^{-1} \end{bmatrix}$$

Mathematical Criteria for Network Quality Evaluation

1. Precision Criteria (Scalar Measures)

- **A-Optimality (Trace Criterion):** Minimizes the average variance of the coordinate parameters.

$$\mathrm{Trace}(\mathbf{C}_x) = \sum_{i=1}^{u} \sigma_{x_i}^2 \rightarrow \mathrm{Minimum}$$

- **D-Optimality (Determinant Criterion):** Minimizes the overall volume of the joint confidence ellipsoid.

$$\det(\mathbf{C}_x) \rightarrow \mathrm{Minimum}$$

For engineering stakeout, the semi-major axis \(a\) must be less than the design tolerance divided by the expansion factor chosen for your target confidence level (e.g., a 95% confidence level requires scaling the standard error ellipse by a factor of 2.45).

2. Geometric Criteria (The Error Ellipse)

For any 2D point, the horizontal coordinate covariance sub-matrix is:

$$\mathbf{C}_{\mathrm{point}} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{yx} & \sigma_y^2 \end{bmatrix}$$

The dimensions and orientation of the **Standard Error Ellipse** are derived using eigenvalues and eigenvectors:

- **Semi-major axis (a):**

$$a^2 = \frac{1}{2}\left(\sigma_x^2 + \sigma_y^2 + \sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^2}\right)$$

- **Semi-minor axis (b):**

$$b^2 = \frac{1}{2}\left(\sigma_x^2 + \sigma_y^2 - \sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^2}\right)$$

- **Orientation Angle (θ from North):**

$$\tan(2\theta) = \frac{2\sigma_{xy}}{\sigma_x^2 - \sigma_y^2}$$

3. Internal Reliability and Redundancy

A network can be precise but weak against undetected gross errors (blunders). **Internal reliability** measures the size of the marginally detectable blunder ($\nabla_0 l_i$).

The **Redundancy Matrix ($\mathbf{R}$)** is defined as:

$$\mathbf{R} = \mathbf{I} - \mathbf{A}(\mathbf{A}^T\mathbf{P}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{P}$$

The diagonal elements r_i (redundancy numbers) range between $0 \le r_i \le 1$. They indicate how well an observation is checked by the surrounding network geometry.

- If $r_i \to 0$, the observation is uncontrolled. A blunder here cannot be detected and will directly warp the stakeout.
- If $r_i \ge 0.35$, the network geometry is considered robust enough to isolate systematic errors.

Theoretical Breakdown of Accuracy Levels by Tier

Civil and structural engineering tolerances govern the required geodetic network tier. Below is the theoretical breakdown of the mathematical limits for each level.

Tier 1: Sub-Millimeter Metrology Networks

- **Applications:** Particle accelerators, turbine alignments, high-speed rail tracks, aerospace manufacturing templates.
- **Mathematical Boundary:** $\sigma_{x,y} \leq \pm 1.0$ mm, $\sigma_z \leq \pm 0.5$ mm. Relative precision $> 1 : 500,000$.
- **Geometric Requirements:** Ultra-redundant braced configurations with inter-visible stations. Network configuration must avoid grazing sights near thermal surfaces to prevent refraction distortion.
- **Stochastic Profile:** Laser trackers or sub-second ($\sigma_\alpha = 0.5''$) total stations. Forced-centering pillars are mandatory to eliminate human centering error ($\sigma_{\text{center}} \to 0$).

Tier 2: Precision Engineering and Structural Networks

- **Applications:** High-rise structures, long-span suspension bridges, deep rail tunnels.
- **Mathematical Boundary:** $\sigma_{x,y} = \pm 2.0$ mm to ± 5.0 mm, $\sigma_z = \pm 1.0$ mm to ± 2.0 mm. Relative precision $1 : 100,000$ to $1 : 200,000$.
- **Geometric Requirements:** Core control networks fixed with robust external reference datums. In tunnels, this requires zig-zag traverse structures with gyroscopic azimuth constraints to control lateral error drift.
- **Stochastic Profile:** 1" robotic total stations combined with static dual-frequency GNSS networks (minimum 1-hour sessions to resolve carrier phase ambiguities). Precise digital leveling loops with invar rods.

Tier 3: Standard Civil Infrastructure Networks

- **Applications:** Commercial developments, multi-story buildings, local highway pavements, bridge approach ramps.
- **Mathematical Boundary:** $\sigma_{x,y} = \pm 5.0$ mm to ± 10.0 mm, $\sigma_z = \pm 5.0$ mm. Relative precision $1 : 20,000$ to $1 : 50,000$.
- **Geometric Requirements:** Open/closed traverses tied to regional public control networks (datums).
- **Stochastic Profile:** 3" total stations and real-time GNSS Network RTK or PPP configurations.

Tier 4: Bulk Earthworks and Utility Networks

- **Applications:** Site grading, drainage lines, cut-and-fill calculations, preliminary corridor clearing.
- **Mathematical Boundary:** $\sigma_{x,y} = \pm 15.0$ mm to ± 25.0 mm, $\sigma_z = \pm 20.0$ mm to ± 50 mm. Relative precision $1 : 5,000$ to $1 : 10,000$.
- **Geometric Requirements:** Sparse baselines optimized primarily for speed and area coverage.
- **Stochastic Profile:** Single-baseline GNSS RTK or machine automation sensors attached directly to excavators or graders.

Observation Planning: How Many Measurements Are Enough?

General Principle

Required network accuracy:

$$\sigma_{network} \leq \sigma_{required}$$

Observation precision improves with repeated measurements:

$$\sigma_{mean} = \frac{\sigma_{obs}}{\sqrt{n}}$$

where:

- n = number of observation series
- σ_{obs} = precision of a single observation

General Observation Planning Model

Required number of observation series:

$$n \geq \left(\frac{\sigma_{instrument}}{\sigma_{required}}\right)^2$$

where:

$$\sigma_{instrument} = f(d, i, s, t, anceanglecenteringtargetsetup)$$

Angular Observations (Total Station)

Required number of series:

$$n \geq \left(\frac{\sigma_{\alpha}}{\sigma_{required}}\right)^2$$

where:

- σ_{α} = angular precision of the instrument
- $\sigma_{required}$ = required angular precision

Distance Observations (EDM)

EDM precision model:

$$\sigma_D = \sqrt{a^2 + b^2 D^2}$$

where:

- a = constant term (mm)
- b = ppm term
- D = measured distance

Required number of series:

$$n \geq \left(\frac{\sigma_D}{\sigma_{required}}\right)^2$$

Practical Conclusion

The required number of measurements depends not only on instrument accuracy, but on the complete measurement system and required engineering tolerances.

OBSERVATION PLANNING – PRACTICAL FLOW

1 DEFINE REQUIRED ACCURACY

- Determine required accuracy for points, distances, angles, or other parameters.
- Based on engineering tolerances and project specifications.

2 SELECT INSTRUMENT

- Choose instrument according to required accuracy.
- Check instrument specifications (angular and distance precision).

3 ESTIMATE PRECISION PER OBSERVATION

- Estimate single observation precision (σ_{obs}).
- Consider distance, angle, centering, target, and setup conditions.
- Use instrument model:

$$\sigma_D = \sqrt{a^2 + (bD)^2}$$

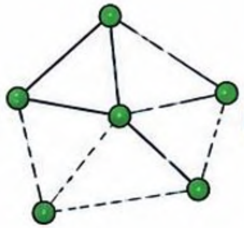
$$\sigma_\alpha = \text{instrument spec}$$

4 COMPUTE NUMBER OF SERIES

- Minimum number of observation series (n) to achieve required accuracy:

$$n \geq \left(\frac{\sigma_{obs}}{\sigma_{req}}\right)^2$$

5 PERFORM A PRIORI ANALYSIS



- Build mathematical model of the network.
- Use estimated σ_{obs} and n.
- Compute expected standard deviations of points and parameters ($Q_x = (A^T PA)^{-1}$).
- Check if $\sigma_{network} \leq \sigma_{req}$.

6 OBSERVE THE NETWORK

- Perform observations using the planned number of series.
- Ensure good field practice and data quality.

7 ADJUSTMENT & QUALITY CHECK

- Adjust the observations.
- Check residuals and standard deviations.
- Verify that achieved accuracy meets requirements.
- If not, repeat with additional observations.

SOURCES OF ERRORS

(Affecting Single Observation Accuracy)

Instrument Precision + Centering Error + Target Error + Setup Error + Environmental Conditions

COMPUTE NUMBER OF SERIES

$$n \geq \left(\frac{\sigma_{obs}}{\sigma_{req}}\right)^2$$

where:

σ_{obs} = single observation precision

σ_{req} = required precision

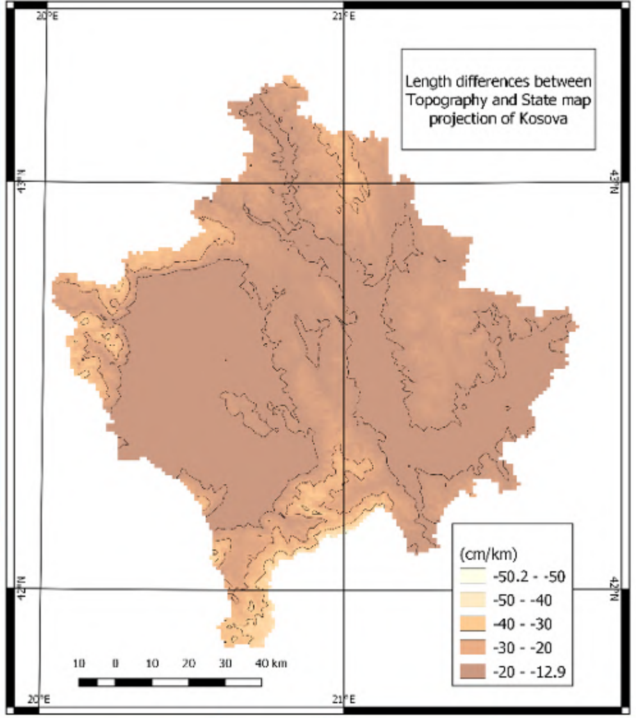
n = number of observation series

DECISION BASED ON A PRIORI ANALYSIS

- ✓ If $\sigma_{network} \leq \sigma_{req}$ → Proceed to observations
- ✓ If $\sigma_{network} > \sigma_{req}$ → Increase n or improve setup
- ✓ Optimize network geometry if needed
- ✓ Balance accuracy, time, and cost

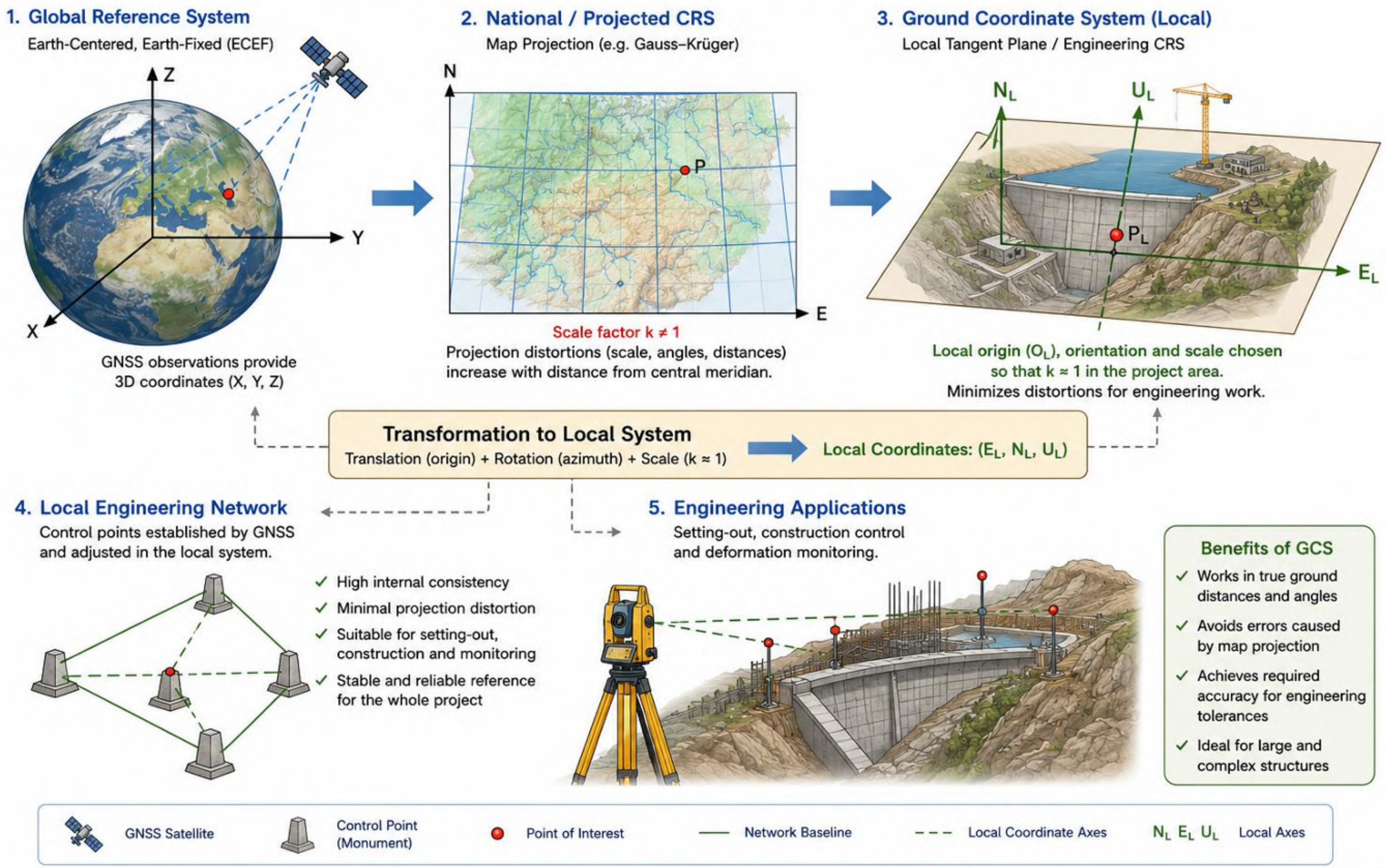
GOAL: ACHIEVE REQUIRED ACCURACY WITH OPTIMAL EFFORT

Right accuracy – Right method – Right measurement – Right result



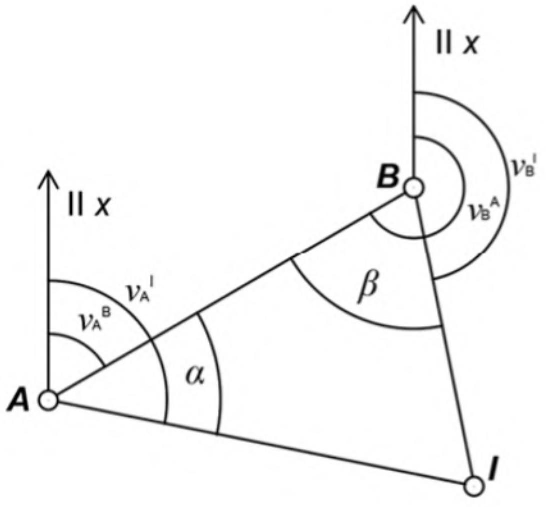
Distortion Range (cm/km)	ppm	Kosovaref01 (km²)	Kosovaref01 (%)
12.9-15	129-150	768	7.1%
15-20	150-200	3848	35.3%
20-25	200-250	3789	34.8%
25-30	250-300	1288	11.8%
30-40	300-400	1006	9.2%
40-50	400-500	192	1.76%
>50	>500	2	0.02%

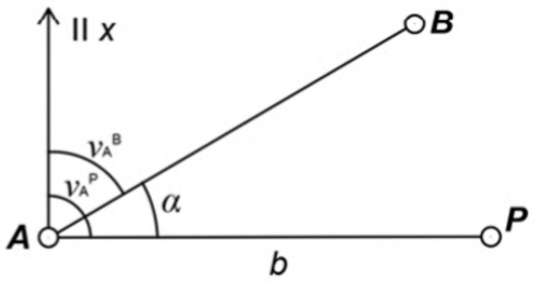
Ground Coordinate System

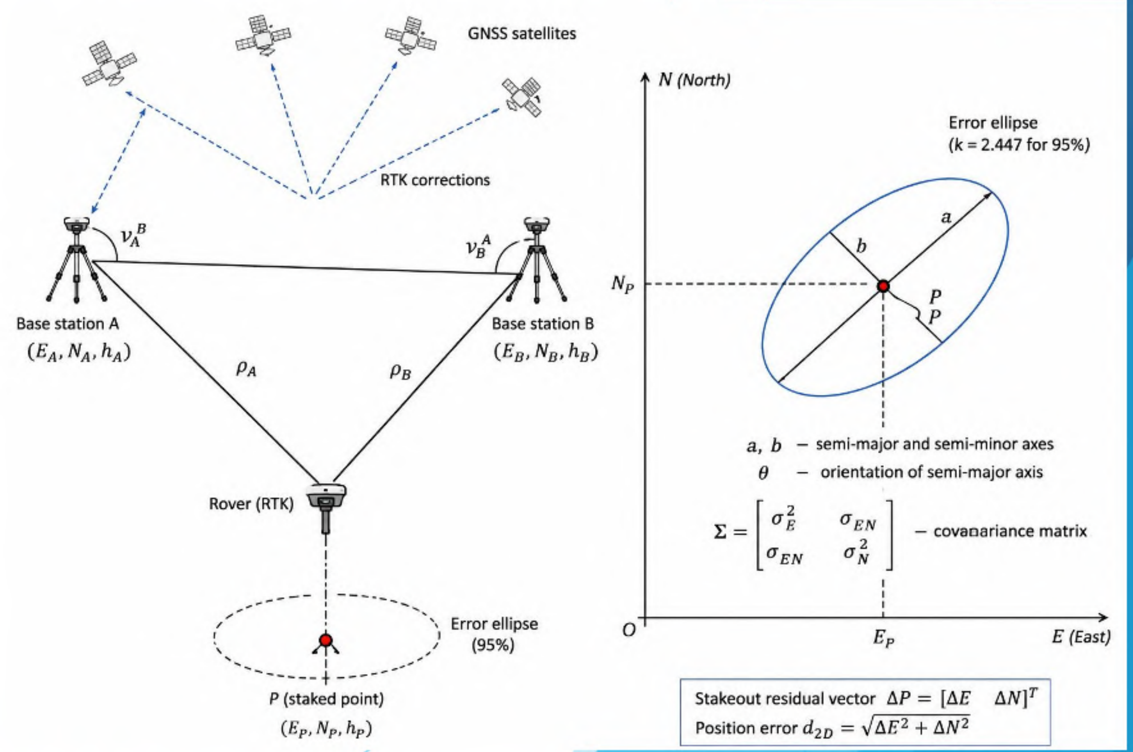


STAKEOUT AND ERROR ELLIPSES

- horizontal stakeout by the method of the intersection of the sight lines,
- horizontal stakeout by the polar method, and
- horizontal stakeout by the GPS/RTK method.







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Horizontal stakeout by the method of the intersection of the sight lines

To calculate the horizontal stakeout quality for the intersection method, it is necessary to start from the equation for calculating the coordinates of points using the method of the intersection:

$$y_I = y_A + \Delta y = y_A + \overline{AI}\sin\nu_A^I = y_A + \overline{AB}\frac{\sin\beta}{\sin(\alpha+\beta)}\sin(\nu_A^B+\alpha),$$

$$x_I = x_A + \Delta x = x_A + \overline{AI}\cos\nu_A^I = x_A + \overline{AB}\frac{\sin\beta}{\sin(\alpha+\beta)}\cos(\nu_A^B+\alpha),$$

or for control:

$$y_I = y_B + \Delta y = y_B + \overline{BI}\sin\nu_B^I = y_B + \overline{AB}\frac{\sin\alpha}{\sin(\alpha+\beta)}\sin(\nu_B^A-\beta),$$

$$x_I = x_B + \Delta x = x_B + \overline{BI}\cos\nu_B^I = x_B + \overline{AB}\frac{\sin\alpha}{\sin(\alpha+\beta)}\cos(\nu_B^A-\beta),$$

where:

$$\frac{\overline{AI}}{\overline{AB}} = \frac{\sin\beta}{\sin(180^\circ-(\alpha+\beta))} = \frac{\sin\beta}{\sin(\alpha+\beta)}$$

$$\frac{\overline{BI}}{\overline{AB}} = \frac{\sin\alpha}{\sin(180^\circ-(\alpha+\beta))} = \frac{\sin\alpha}{\sin(\alpha+\beta)}$$

$$\nu_A^I = \nu_A^B + \alpha \text{ and } \nu_B^I = \nu_B^A - \beta$$

$$\sigma_{y_I} = \sqrt{\overline{AB}^2\left(\frac{\cos(2\beta-\nu_A^B)-\cos\nu_A^B}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\alpha^2 + \overline{AB}^2\left(\frac{\cos\nu_A^B-\cos(2\alpha+\nu_A^B)}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\beta^2},$$

$$\sigma_{x_I} = \sqrt{\overline{AB}^2\left(\frac{\sin(2\beta-\nu_A^B)+\sin\nu_A^B}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\alpha^2 + \overline{AB}^2\left(\frac{\sin(2\alpha+\nu_A^B)-\sin\nu_A^B}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\beta^2},$$

or for control:

$$\sigma_{y_I} = \sqrt{\overline{AB}^2\left(\frac{\cos(2\beta-\nu_B^A)-\cos\nu_B^A}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\alpha^2 + \overline{AB}^2\left(\frac{\cos\nu_B^A-\cos(2\alpha+\nu_B^A)}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\beta^2},$$

$$\sigma_{x_I} = \sqrt{\overline{AB}^2\left(\frac{\sin(2\beta-\nu_B^A)+\sin\nu_B^A}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\alpha^2 + \overline{AB}^2\left(\frac{\sin(2\alpha+\nu_B^A)-\sin\nu_B^A}{\cos(2\alpha+2\beta)-1}\right)^2\sigma_\beta^2},$$

where:

σ_α and σ_β … the standard deviations of angles α and β.

In order to compute the error ellipse of the stakeout, the covariance must also be determined σ_{yx1}:

$$\sigma_{yx_I} = -\frac{\overline{AB}^2\{[\sin(2\nu_A^B)+2\sin(2\beta-2\nu_A^B)-\sin(4\beta-2\nu_A^B)]\sigma_\alpha^2+[\sin(2\nu_A^B)-2\sin(2\alpha+2\nu_A^B)+\sin(4\alpha+2\nu_A^B)]\sigma_\beta^2\}}{\cos(4\alpha+4\beta)-4\cos(2\alpha+2\beta)+3},$$

or for control:

$$\sigma_{yx_I} = -\frac{\overline{AB}^2\{[\sin(2\nu_B^A)+2\sin(2\beta-2\nu_B^A)-\sin(4\beta-2\nu_B^A)]\sigma_\alpha^2+[\sin(2\nu_B^A)-2\sin(2\alpha+2\nu_B^A)+\sin(4\alpha+2\nu_B^A)]\sigma_\beta^2\}}{\cos(4\alpha+4\beta)-4\cos(2\alpha+2\beta)+3}.$$

Horizontal stakeout by the polar method

To calculate the horizontal stakeout quality using the polar method, it is necessary to start from the equation for calculating the coordinates of points using the polar method

$$y_P = y_A + \Delta y = y_A + \overline{AP}\sin\nu_A^P = y_A + \overline{AP}\sin(\nu_A^B + \alpha),$$
$$x_P = x_A + \Delta x = x_A + \overline{AP}\cos\nu_A^P = x_A + \overline{AP}\cos(\nu_A^B + \alpha),$$

or for control:

$$y_P = y_B + \Delta y = y_B + \overline{BP}\sin\nu_B^P = y_B + \overline{BP}\sin(\nu_B^A - \beta),$$
$$x_P = x_B + \Delta x = x_B + \overline{BP}\cos\nu_B^P = x_B + \overline{BP}\cos(\nu_B^A - \beta),$$

By applying the Law of propagation of variances and covariances, the precision of determining the y-coordinate of point P, σ_{y_P}, and the x-coordinate of point P, σ_{x_P}, is obtained:

$$\sigma_{y_P} = \sqrt{\sin^2(\alpha + \nu_A^B)\,\sigma_{\overline{AP}}^2 + \overline{AP}^2\cos^2(\alpha + \nu_A^B)\sigma_\alpha^2},$$

$$\sigma_{x_P} = \sqrt{\cos^2(\alpha + \nu_A^B)\,\sigma_{\overline{AP}}^2 + \overline{AP}^2\sin^2(\alpha + \nu_A^B)\sigma_\alpha^2},$$

$\sigma_{\overline{AP}}$ … the standard deviation of distance $\overline{AP}$.

If the Law of propagation of variances and covariances is applied to the control equations

$$\sigma_{y_P} = \sqrt{\sin^2(\beta - \nu_B^A)\,\sigma_{\overline{BP}}^2 + \overline{BP}^2\cos^2(\beta - \nu_B^A)\sigma_\beta^2},$$

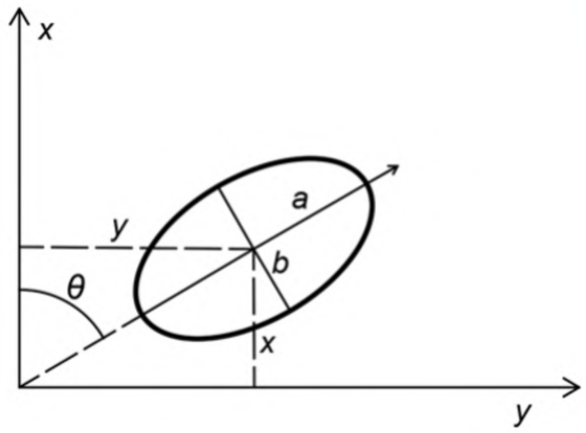
$$\sigma_{x_P} = \sqrt{\cos^2(\beta - \nu_B^A)\,\sigma_{\overline{BP}}^2 + \overline{BP}^2\sin^2(\beta - \nu_B^A)\sigma_\beta^2},$$

$\sigma_{\overline{BP}}$ … the standard deviation of distance $\overline{BP}$, The error ellipses has to be calculated before stakeout and after stakeout for every point of the construction according to the following equations:

$$a = \sigma_0 \sqrt{\frac{\sigma_y^2 + \sigma_x^2 + z}{2}},$$

$$b = \sigma_0 \sqrt{\frac{\sigma_y^2 + \sigma_x^2 - z}{2}},$$

$$\Theta = \frac{1}{2} \operatorname{atan} \frac{2\sigma_{yx}}{\sigma_x^2 - \sigma_y^2},$$



where:

σ_0 … the a priori reference standard deviation (typically equal to 1),

$$z = \sqrt{\left(\sigma_x^2 - \sigma_y^2\right)^2 + 4\sigma_{yx}^2}.$$

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Horizontal stakeout by GPS/RTK

For **GPS/RTK GNSS stakeout**, the mathematical model is simpler than polar/angle stakeout, because the point is positioned directly from GNSS coordinates. The error ellipse is derived from the **2D covariance matrix** of the staked point, similar to the approach used in the uploaded paper, where stakeout quality is predicted and evaluated through expected and achieved error ellipses.

1. Coordinate stakeout model with GPS/RTK

Let the designed point be:

$$P_D = \begin{bmatrix} E_D \\ N_D \end{bmatrix}$$

The RTK/GNSS measured or staked position is:

$$P_G = \begin{bmatrix} E_G \\ N_G \end{bmatrix}$$

The stakeout residual vector is:

$$\Delta P = \begin{bmatrix} \Delta E \\ \Delta N \end{bmatrix} = \begin{bmatrix} E_G - E_D \\ N_G - N_D \end{bmatrix}$$

The horizontal stakeout deviation is:

$$d_{2D} = \sqrt{(\Delta E)^2 + (\Delta N)^2}$$

Stakeout is acceptable if:

$$d_{2D} \leq T$$

where T is the permitted construction tolerance.

2. Covariance model for GPS stakeout

For RTK GNSS, the horizontal covariance matrix is:

$$\Sigma_{EN} = \begin{bmatrix} \sigma_E^2 & \sigma_{EN} \\ \sigma_{EN} & \sigma_N^2 \end{bmatrix}$$

where:

$$\sigma_E = standard\ deviation\ in\ Easting$$
$$\sigma_N = standard\ deviation\ in\ Northing$$
$$\sigma_{EN} = \rho \sigma_E \sigma_N$$

and ρ is the correlation coefficient between Easting and Northing.

If project coordinates also have uncertainty, then:

$$\Sigma_\Delta = \Sigma_{GNSS} + \Sigma_{design} + \Sigma_{control}$$

For practical RTK stakeout, often:

$$\Sigma_\Delta \approx \Sigma_{GNSS}$$

if design and control coordinates are treated as fixed.

3. Error ellipse for GPS stakeout

The semi-major and semi-minor axes are obtained from the eigenvalues of the covariance matrix:

$$\lambda_{1,2} = \frac{\sigma_E^2 + \sigma_N^2}{2} \pm \sqrt{\left(\frac{\sigma_E^2 - \sigma_N^2}{2}\right)^2 + \sigma_{EN}^2}$$

Then:

$$a = k\sqrt{\lambda_1}$$
$$b = k\sqrt{\lambda_2}$$

where:

$$a = semi{-}major\ axis$$
$$b = semi{-}minor\ axis$$
$$k = confidence\ factor$$

Typical values:

$$k = 1.00\ for\ standard\ ellipse$$

k=2.447 \quad \text{for 95% confidence ellipse in 2D}

4. Orientation of the error ellipse

The orientation angle of the ellipse is:

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{2\sigma_{EN}}{\sigma_E^2 - \sigma_N^2}\right)$$

This angle defines the direction of the semi-major axis relative to the Easting axis.

5. Practical GPS/RTK stakeout quality model

For each stakeout point:

$$P_i = (E_i, N_i)$$

compute:

$$d_i = \sqrt{\left(E_{G_i} - E_{D_i}\right)^2 + \left(N_{G_i} - N_{D_i}\right)^2}$$

and:

$$\Sigma_i = \begin{bmatrix} \sigma_{E_i}^2 & \sigma_{EN_i} \\ \sigma_{EN_i} & \sigma_{N_i}^2 \end{bmatrix}$$

Then calculate:

$$a_i,\ b_i,\ \theta_i$$

The point is acceptable if:

$$d_i \le T$$

and preferably also:

$$a_{95,i} \le T$$

VERTICAL STAKEOUT ACCURACY MODEL

1. Leveling instrument model

Designed elevation:

$$H_D$$

Measured elevation:

$$H_L$$

Vertical stakeout residual:

$$\Delta H_L = H_L - H_D$$

Distance-dependent leveling accuracy:

$$\sigma_{H_L} = \sigma_{1km}\sqrt{L}$$

where $L$is leveling distance in km.

95% vertical confidence interval:

$$CI_{95,L} = \pm 1.96\sigma_{H_L}$$

Acceptance condition:

$$|\Delta H_L| \leq T_V$$

This is the most precise model for vertical construction stakeout.

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2. Total station model

Designed elevation:

$$H_D$$

Elevation from total station:

$$H_{TS} = H_A + h_i + s\cos z - h_p$$

where:

$$H_A = known\ station\ elevation$$
$$h_i = instrument\ height$$
$$s = slope\ distance$$
$$z = zenith\ angle$$
$$h_p = prism\ height$$

Vertical residual:

$$\Delta H_{TS} = H_{TS} - H_D$$

Error propagation:

$$\sigma_{H_{TS}}^2 = \sigma_{H_A}^2 + \sigma_{h_i}^2 + \cos^2 z\,\sigma_s^2 + s^2\sin^2 z\,\sigma_z^2 + \sigma_{h_p}^2$$

95% confidence interval:

$$CI_{95,TS} = \pm 1.96\sigma_{H_{TS}}$$

Acceptance condition:

$$|\ \Delta H_{TS}\ | \leq T_V$$

3. GPS / RTK GNSS model

Designed elevation:

$$H_D$$

GNSS ellipsoidal height:

$$h_{GNSS}$$

Geoid undulation:

$$N$$

Orthometric height:

$$H_{GNSS} = h_{GNSS} - N$$

Vertical residual:

$$\Delta H_{GNSS} = H_{GNSS} - H_D$$

Variance model:

$$\sigma_{H_{GNSS}}^2 = \sigma_{h_{GNSS}}^2 + \sigma_N^2$$

If antenna height is included:

$$\sigma_{H_{GNSS}}^2 = \sigma_{h_{GNSS}}^2 + \sigma_N^2 + \sigma_{h_a}^2$$

95% confidence interval:

$$CI_{95,GNSS} = \pm 1.96\sigma_{H_{GNSS}}$$

Acceptance condition:

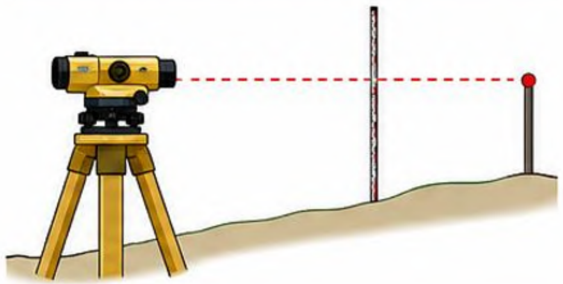
$$|\ \Delta H_{GNSS}\ | \leq T_V$$

For RTK, vertical accuracy is usually weaker than horizontal accuracy, so GNSS is less suitable than leveling for strict vertical construction tolerances.

Which Method Should Be Used?

LEVELING

Highest Vertical Accuracy

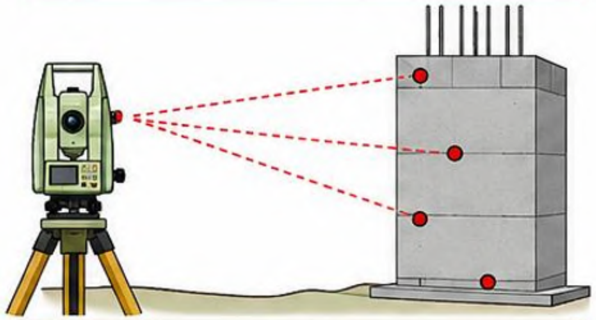


- Precise height determination
- Long range capability
- Not affected by short-term atmospheric conditions
- Slower field work

Best choice when vertical accuracy is critical

TOTAL STATION

High Local Precision

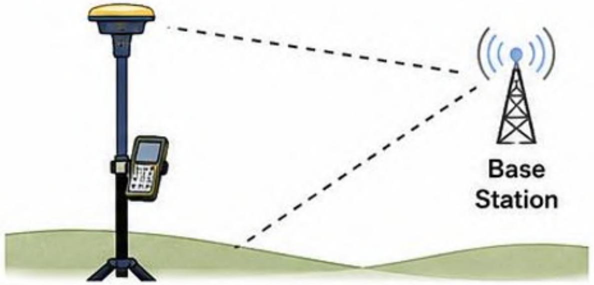


- High angular and distance accuracy
- Ideal for local control and staking
- Suitable for deformation monitoring
- Moderate field time

Best choice for most construction and monitoring tasks

RTK GNSS

Fast Field Operations



- Rapid point determination
- Efficient for large areas
- Lower precision than total station and leveling
- Dependent on satellite availability and corrections

Best choice when speed and efficiency are priorities

General Rule: Use the method that satisfies the required accuracy with the least field time and resources.

GEODETIC DEFORMATION ANALYSES

Objective

Separate:

Observed $Changes = True\ Deformation + Random\ Errors$

Main problem:

Two epochs:

$$Epoch_1 \rightarrow Epoch_2$$

Determine:

- Which points are stable?
- Which points moved?
- How significant is movement?

General Adjustment Model

Observation equations:

$$Ax + v = l$$

Adjustment:

$$\hat{x} = (A^T PA)^{-1} A^T Pl$$

Deformation vector:

$$d = x_2 - x_1$$

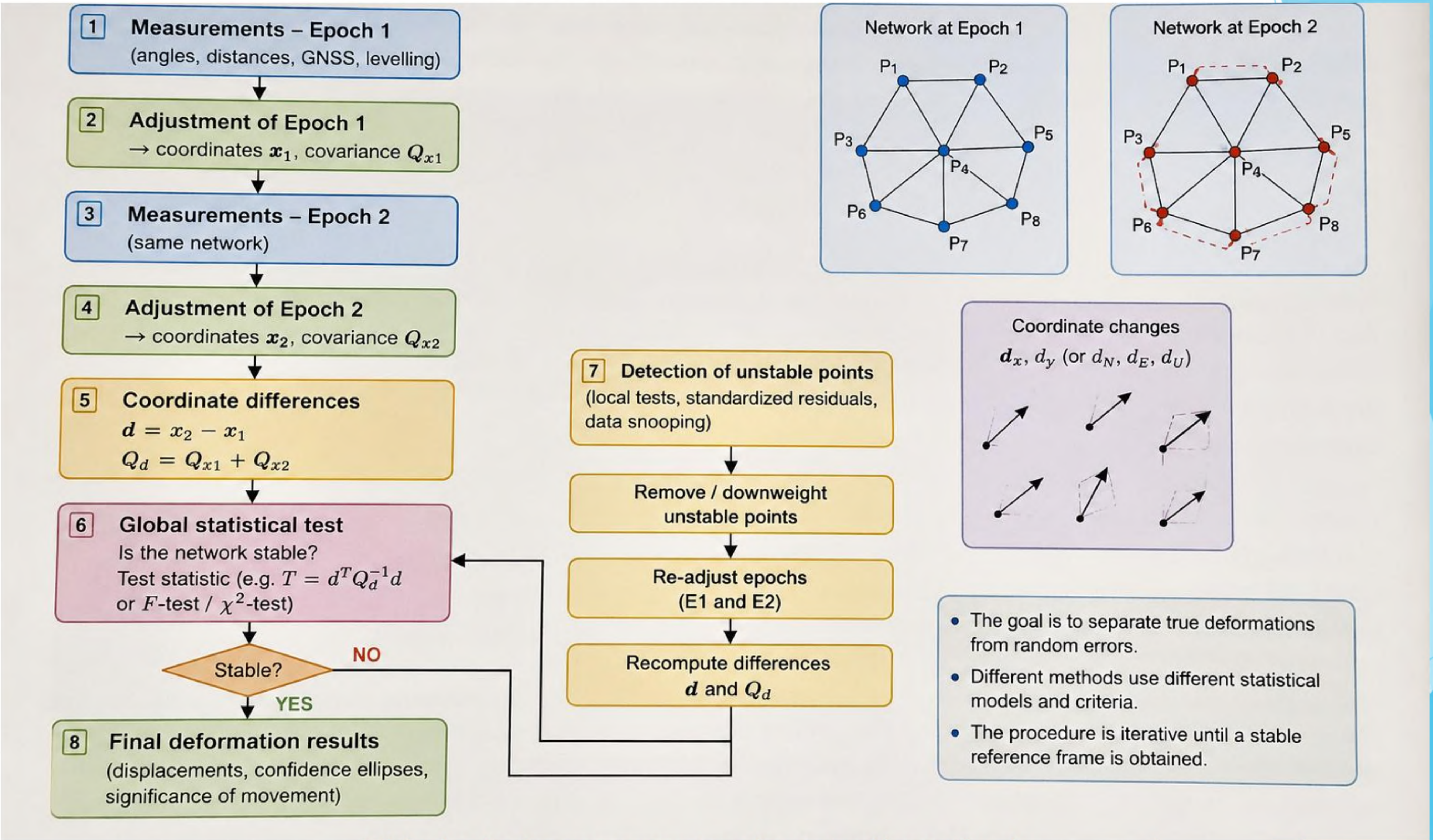
Covariance:

$$Q_d = Q_{x1} + Q_{x2}$$

"testing whether H_0:*d=0*"

Testing whether displacement vector equals zero.

Typical Deformation Analysis Procedure



This logic is common to almost all methods.

Pelzer Method (Hannover School)

Step 1
Assume reference points stable
Step 2
Compute deformation vector

$$d = x_2 - x_1$$

Test statistic:

$$T = \frac{d^T Q_d^{-1} d}{h\sigma_0^2}$$

Decision:
If:

$$T > F_\alpha$$

↓
Network not stable

Step 3
Localize unstable points
Remove suspect point
Recompute: A,B,C,D,E

↓

remove B

↓

A,C,D,E

↓

test again
Repeat until Global test accepted!

Iteratively eliminate the point with the largest contribution to instability until the global test is accepted.

Practical Use
✓ Dams
✓ Bridges
✓ Buildings
✓ Monitoring with stable monuments

Caspary Method

Core principle:
Direct testing of coordinate changes.
Statistic:

$$w = d^T Q_d^{-1} d$$

Decision:

$$w > \chi^2$$

↓
movement detected

Procedure:

Compute coordinate changes

↓

Test significance

↓

Point stable?

YES → keep

NO → deforming point

Point displacement is accepted only if the displacement vector is statistically significant compared with its covariance.

Practical Use
✓ Engineering monitoring
✓ Small-medium networks
✓ Construction control

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Delft Method

Core idea:

Congruency between epochs

Null hypothesis:

$$H_0 : d = 0$$

Compare:

Constrained solution

vs

Free solution

Adjust Both Epochs

Constrained solution

$$v_c^T P v_c$$

(Adjustment with constraints)

↓

Free solution

$$v_f^T P v_f$$

(Adjustment without constraints)

Compare Both Solutions

Statistic:

$$F = \frac{(v_c P v_c - v_f P v_f)/q}{(v_f P v_f)/f}$$

Decision:

$$F > F_{crit}$$

↓

epochs inconsistent

↓

Deformation exists

Congruency test compares constrained and free network solutions between epochs

Practical Use

✓ High precision monitoring

✓ Research networks

✓ Scientific deformation studies

✓ Crustal movement studies

Karlsruhe Method

Problem:
Reference points may also move.
Solution:
Free network adjustment.
Transformation:

$$x_c = x_f - Sk$$

Concept:
Remove datum dependency.

Procedure:

Free adjustment

↓

S transformation

↓

Compute deformation

↓

Reference independent result

Recommended when reference points cannot be assumed stable.

Practical Use

✓ Landslides
✓ Mining subsidence
✓ Large unstable areas
✓ Tectonic monitoring

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YU Method

Practical Use:
✓ Small monitoring networks
✓ Conventional engineering workflows
✓ Existing legacy monitoring systems
✓ Faster calculations

Core Philosophy
Stable coordinate system = stable deformation results
Unlike Pelzer / Delft / Karlsruhe:

- Uses **conventional datum**
- No optimal datum definition
- No S-transformations
- Requires stable coordinate system definition

Number of possible sides:

$$r = \frac{n(n-1)}{2}$$

Test Length Differences
Hypotheses:

$$H_0: \Delta S_i = 0$$
$$H_A: \Delta S_i \neq 0$$

Statistical test:

$$t_i = \frac{\Delta S_i}{\sigma_{\Delta S_i}}$$

Decision:
If:

$$t_i < t_{\alpha/2}$$

↓
Length considered stable
Otherwise:
↓
Reject side

Test Azimuth Differences
Hypotheses:

$$H_0: \Delta \phi_i = 0$$
$$H_A: \Delta \phi_i \neq 0$$

Statistic:

$$t_i = \frac{\Delta \phi_i}{\sigma_{\Delta \phi_i}}$$

Decision:
If:

$$t_i < t_{\alpha/2}$$

↓
Point group considered stable
Otherwise:
↓
Reject candidate group.

Comparison of Practical Applications of Deformation Analysis Methods

Method	Recommended When	Not Recommended When	Typical Applications	Main Strength
Pelzer (Hannover School)	Stable reference points exist and can be reliably identified	Reference points may move or stability is uncertain	Dams, bridges, buildings, classical engineering monitoring	Robust iterative stability testing
Caspary Method	Simple and efficient deformation testing is required	Large unstable networks or uncertain datum conditions	Construction monitoring, industrial monitoring, small-medium networks	Simple implementation with direct significance testing
Delft Method	High statistical rigor and congruency analysis are required	Fast operational projects with limited computational resources	Scientific monitoring, crustal deformation, research networks	Strong statistical framework
Karlsruhe Method	Reference point stability cannot be guaranteed	Small simple projects with clearly stable control points	Landslides, mining subsidence, tectonic monitoring	Datum-independent deformation estimation
Former Yugoslav School	Conventional datum and stable coordinate systems are available	Stable datum cannot be confirmed	Classical monitoring networks, legacy engineering workflows	Faster computations and simpler implementation

No universal best method exists.

Method selection depends primarily on:

- Reference point stability
- Network geometry
- Required statistical rigor
- Type of engineering object

Multi-Temporal InSAR Method (PSInSAR / QPSInSAR)

Core Philosophy

Deformation is estimated from phase differences between repeated SAR acquisitions

Unlike classical geodetic methods:

- No physical network required
- Millions of monitoring points possible
- Spatially continuous monitoring
- Large-area deformation mapping possible

Step 1 – Acquire Multi-Temporal SAR Images

Repeated SAR acquisitions:

```
t1 → t2 → t3 → t4 → ... → tn
```

Ascending + Descending orbits frequently used.

Step 2 - Generate Interferograms

Interferometric phase:

$$\Delta\phi = \phi_2 - \phi_1$$

Generate multiple interferograms.

STAR graphs commonly define interferometric connectivity.

Step 3 - Differential Phase Model

Observed phase:

$$\Delta\phi = \Delta\phi_{disp} + \Delta\phi_{topo} + \Delta\phi_{atmo} + \Delta\phi_{noise}$$

where:

•deformation component

•topographic component

•atmospheric component

•noise component

Step 4 - Remove Unwanted Components

Corrections:

✓ orbital corrections

✓ topographic corrections

✓ earth flattening

✓ atmospheric correction (APS)

Result:

$$\Delta\phi \rightarrow \Delta\phi_{disp}$$

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Step 5 - Compute LOS Displacement

LOS displacement:

$$d_{LOS} = \frac{\lambda}{4\pi}\Delta\phi_{disp}$$

where:

•λ= wavelength

•LOS = line of sight displacement

Step 6 - Select Stable Scatterers

Persistent Scatterers (PS)

- stable phase behavior
- buildings
- infrastructure
- rocks

Distributed Scatterers (DS)

- spatially homogeneous areas
- vegetation
- natural surfaces

Step 7 - Time Series Analysis

Estimate:

$$v = \frac{d}{dt}$$

Compute:

- displacement velocity
- nonlinear motion
- seasonal signals
- long-term trends

Step 8 - Interpretation and Validation Objective

Validate deformation results and transform them into engineering information.

Accuracy Assessment

Compare InSAR results with independent measurements:

- GNSS observations
- Leveling measurements
- Total station measurements

Validation Model

Difference between methods:

$$\Delta d = d_{InSAR} - d_{Reference}$$

Compute validation statistics:

$$RMSE = \sqrt{\frac{\sum(d_{InSAR} - d_{Reference})^2}{n}}$$

where:

•d_{InSAR}= InSAR displacement

•$d_{Reference}$= reference displacement

•n= number of validation points

PRACTICAL WORKFLOW

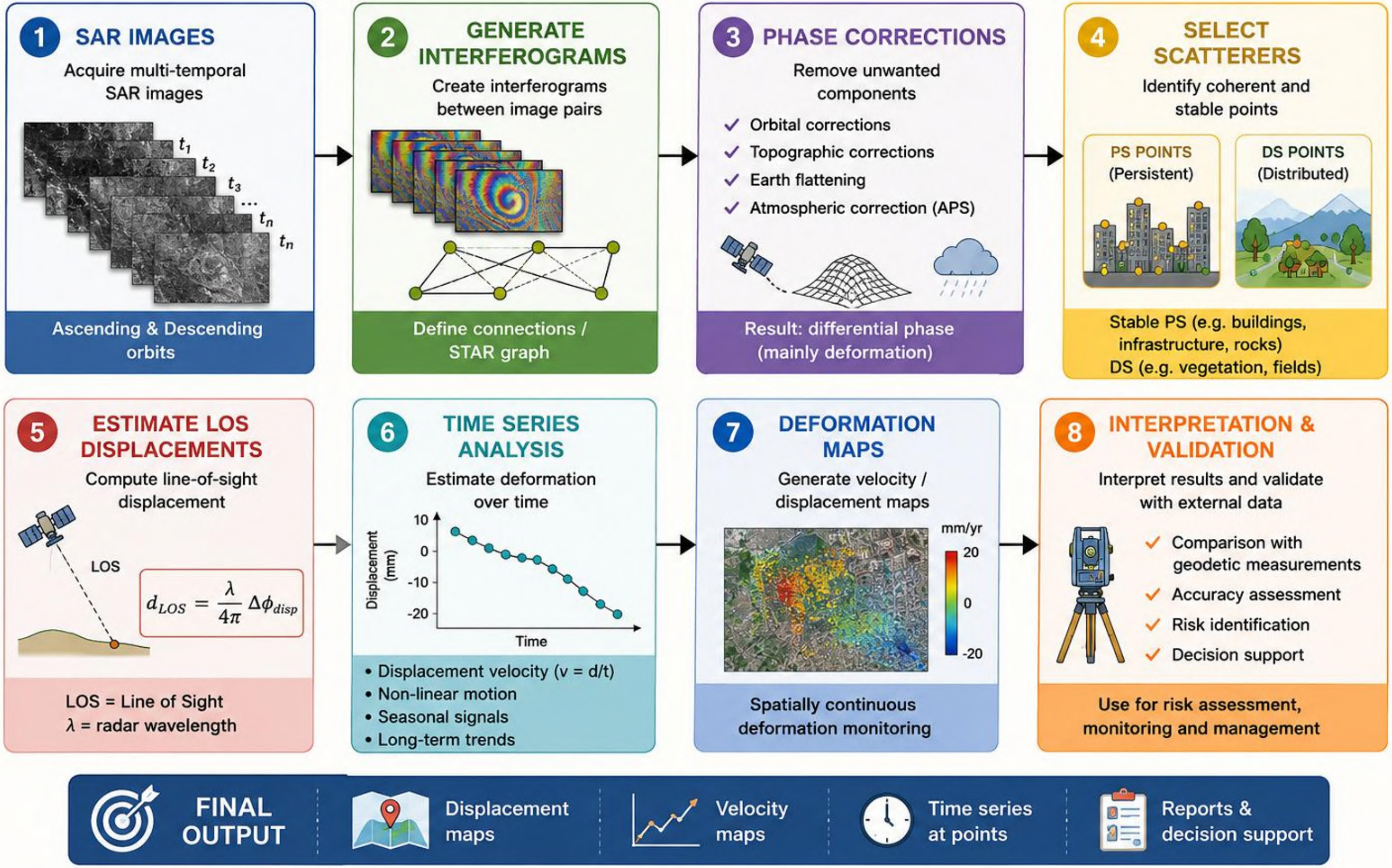
InSAR Deformation Monitoring (PSInSAR / QPSInSAR)

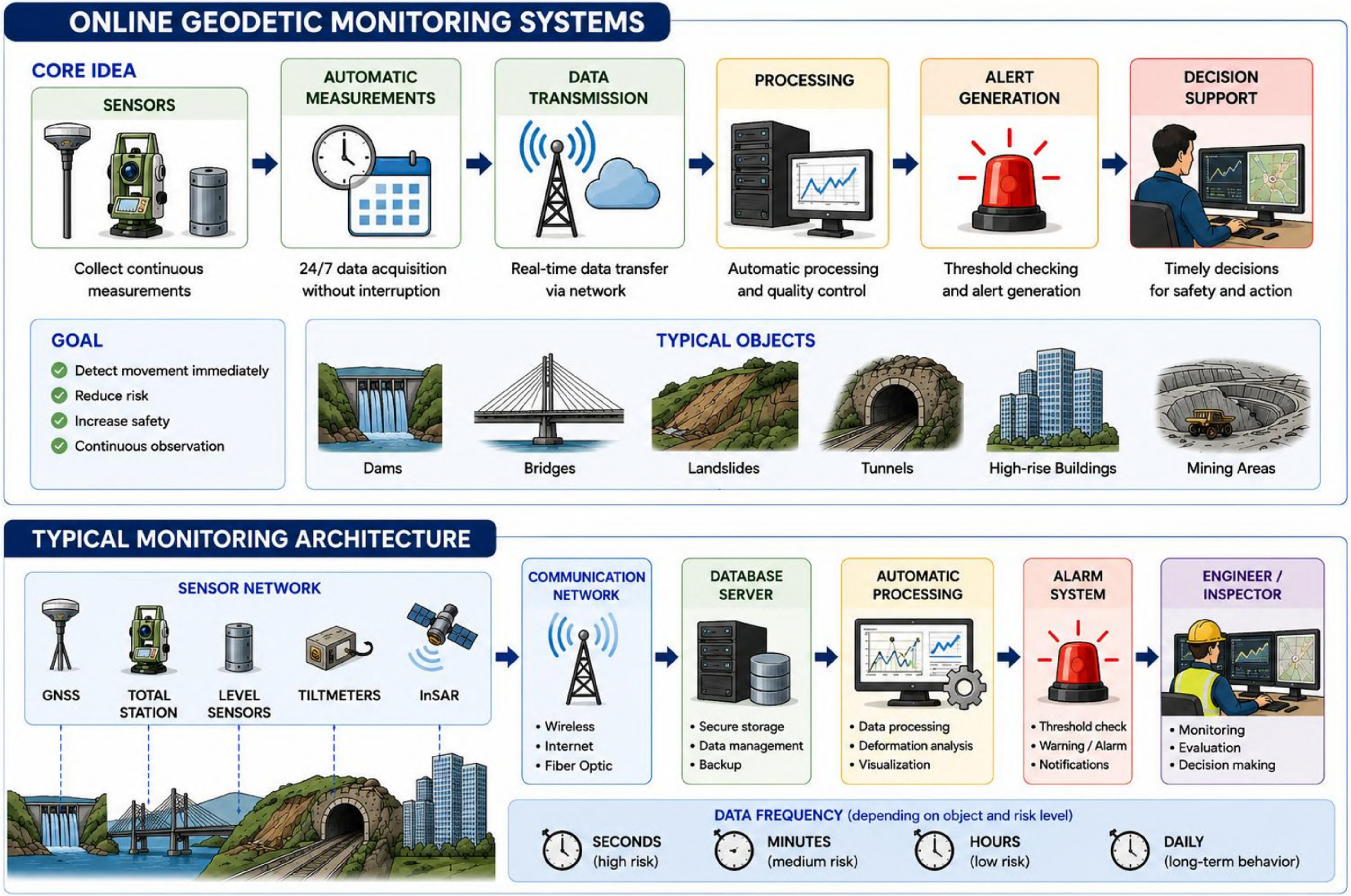
Suitable for:

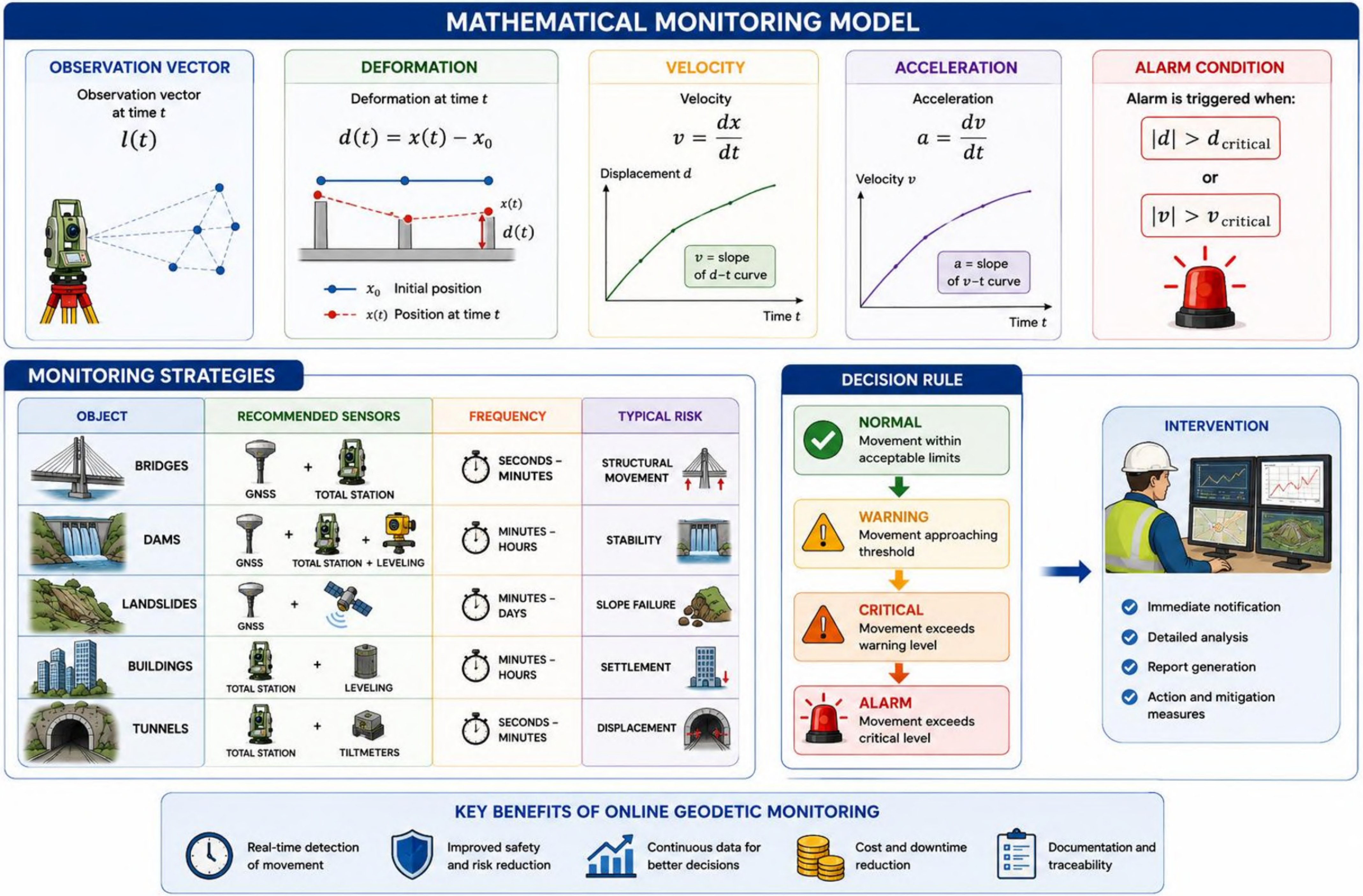
- ✓ Landslides
- ✓ Mining subsidence
- ✓ Urban subsidence
- ✓ Regional tectonics
- ✓ Dam monitoring
- ✓ Large infrastructure monitoring

Less Suitable for:

- ✗ Dense vegetation
- ✗ Rapid decorrelation
- ✗ Need for real-time monitoring
- ✗ North-South displacement sensitivity limitations




ONLINE GEODETIC MONITORING SYSTEMS
CORE IDEA
SENSORS
Collect continuous measurements
AUTOMATIC MEASUREMENTS
24/7 data acquisition without interruption
DATA TRANSMISSION
Real-time data transfer via network
PROCESSING
Automatic processing and quality control
ALERT GENERATION
Threshold checking and alert generation
DECISION SUPPORT
Timely decisions for safety and action
GOAL
Detect movement immediately
Reduce risk
Increase safety
Continuous observation
TYPICAL OBJECTS
Dams
Bridges
Landslides
Tunnels
High-rise Buildings
Mining Areas
TYPICAL MONITORING ARCHITECTURE
SENSOR NETWORK
GNSS
TOTAL STATION
LEVEL SENSORS
TILTMETERS
InSAR
COMMUNICATION NETWORK
• Wireless
• Internet
• Fiber Optic
DATABASE SERVER
• Secure storage
• Data management
• Backup
AUTOMATIC PROCESSING
• Data processing
• Deformation analysis
• Visualization
ALARM SYSTEM
• Threshold check
• Warning / Alarm
• Notifications
ENGINEER / INSPECTOR
• Monitoring
• Evaluation
• Decision making
DATA FREQUENCY (depending on object and risk level)
SECONDS (high risk)
MINUTES (medium risk)
HOURS (low risk)
DAILY (long-term behavior)


MATHEMATICAL MONITORING MODEL
OBSERVATION VECTOR
Observation vector at time t
$l(t)$
DEFORMATION
Deformation at time t
$d(t) = x(t) - x_0$
$x(t)$
$d(t)$
x_0 Initial position
$x(t)$ Position at time t
VELOCITY
Velocity
$v = \frac{dx}{dt}$
Displacement d
v = slope of d–t curve
Time t
ACCELERATION
Acceleration
$a = \frac{dv}{dt}$
Velocity v
a = slope of v–t curve
Time t
ALARM CONDITION
Alarm is triggered when:
$|d| > d_{critical}$
or
$|v| > v_{critical}$
MONITORING STRATEGIES
OBJECT
RECOMMENDED SENSORS
FREQUENCY
TYPICAL RISK
BRIDGES
GNSS + TOTAL STATION
SECONDS – MINUTES
STRUCTURAL MOVEMENT
DAMS
GNSS + TOTAL STATION + LEVELING
MINUTES – HOURS
STABILITY
LANDSLIDES
GNSS +
MINUTES – DAYS
SLOPE FAILURE
BUILDINGS
TOTAL STATION + LEVELING
MINUTES – HOURS
SETTLEMENT
TUNNELS
TOTAL STATION + TILTMETERS
SECONDS – MINUTES
DISPLACEMENT
DECISION RULE
NORMAL
Movement within acceptable limits
WARNING
Movement approaching threshold
CRITICAL
Movement exceeds warning level
ALARM
Movement exceeds critical level
INTERVENTION
Immediate notification
Detailed analysis
Report generation
Action and mitigation measures
KEY BENEFITS OF ONLINE GEODETIC MONITORING
Real-time detection of movement
Improved safety and risk reduction
Continuous data for better decisions
Cost and downtime reduction
Documentation and traceability

CATEGORIZATION OF STRUCTURES AND PROJECT PHASES

EVERY PROJECT MUST PASS THROUGH ALL PHASES: DESIGN – REVISION – IMPLEMENTATION – SUPERVISION

A — CATEGORY A
HIGH CONSEQUENCE STRUCTURES

Structures of high importance and complexity, where failure may result in significant loss of life, economic or environmental impact.

Large Bridges | Dams and Hydraulic Structures | High-Rise and Complex Buildings | Tunnels and Underground Works | Industrial Plants and Facilities

B — CATEGORY B
STANDARD RISK STRUCTURES

Structures of moderate importance and standard complexity, with limited consequences in case of failure.

Residential Buildings (up to 3 stories) | Light Industrial Structures | Roads (not highways) | Neighborhood Leveling (Plaza) | Agricultural Structures

Category A phases

1 DESIGN
- Detailed site investigation
- Geodetic control network design
- Structural design
- Advanced analysis and modeling
- Technical specifications

2 REVISION
- Independent design revision
- Code and standard compliance
- Geodetic accuracy assessment
- Risk analysis
- Approval / comments

3 IMPLEMENTATION
- Precision setting out
- Construction with strict quality control
- Continuous geodetic monitoring
- As-built documentation

4 SUPERVISION
- Independent geodetic supervision
- Continuous monitoring and analysis
- Deviation and risk assessment
- Final acceptance and performance verification

Category B phases

1 DESIGN
- Site investigation and analysis
- Geodetic plan
- Structural design
- Drawings & calculations
- Technical specifications

2 REVISION
- Design check
- Compliance with codes and standards
- Geodetic network verification
- Approval / comments

3 IMPLEMENTATION
- Setting out
- Construction execution
- Geodetic measurements during construction
- As-built documentation

4 SUPERVISION
- Geodetic supervision
- Quality control
- Deviation analysis
- Reports and records
- Final acceptance

KEY PRINCIPLES FOR ALL PROJECTS

SAFETY FIRST — Protecting people, property and the environment.

COMPLIANCE — Meet all legal requirements and technical standards.

QUALITY — Ensure quality in every phase with proper control and documentation.

ROLES & RESPONSIBILITIES — Clear definition of roles for designer, reviewer, contractor and supervisor.

DOCUMENTATION — All phases must be documented, archived and traceable.

CONTINUOUS IMPROVEMENT — Learn from experience and improve processes for future projects.

Bridges | Dams | Buildings | Tunnels | Industrial Plants | Residential | Industrial | Roads | Neighborhood Leveling | Agricultural

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CONCLUSIONS

1. Successful engineering surveying requires integration of network design, measurement planning, stakeout quality control and monitoring strategies.
2. A priori accuracy analysis is essential to prove that geodetic networks can satisfy engineering tolerances before field measurements begin.
3. Local geodetic monitoring networks combined with rigorous adjustment procedures enable reliable detection of structural deformations.
4. Deformation analysis results strongly depend on reference point stability, network geometry and the selected mathematical model.
5. No universal deformation analysis method exists; method selection depends on object type, stability conditions and monitoring objectives.
6. Automated monitoring systems and satellite-based monitoring techniques significantly improve monitoring efficiency and spatial coverage.
7. Early detection and continuous monitoring are fundamental for infrastructure safety, risk reduction and informed engineering decisions.

Pyetje & Diskutime !!!

Faleminderit për vëmendjen!

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