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Challenges and Solutions for Establishing Precise Geodetic Control Networks:
Introducing an Innovative Method

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Network-Aided Reduction of Slope Distances in Small-Scale Geodetic Control Networks

Masoud Shirazian[1]; Mohammad Bagherbandi[2]; and Hamed Karimi[3]

Abstract: Most of the human-made infrastructures (e.g., dams) need very precise geodetic networks and constant monitoring to detect risks of failure and to plan civil engineering maintenance works. The combination of different measurements helps in determining displacements with high precision; therefore, the risk of damages is reduced. In this paper, we present a new approach, which considers a special geodetic observation strategy as a method to significantly reduce the volume of operations of a precise geodetic network and changes the designing concept of such networks. Decrease in data collection time and cost while keeping or increasing the quality of control networks has been one of the most important goals of any network designer. This paper proposes a method exploiting network properties to convert slope distances to the horizontal ones to be used in the classic terrestrial geodetic two-dimensional (2D) networks. We have evaluated the proposed method in different dam geodetic control networks in Iran. The network adjustment results show the acceptable performance of the presented method compared with the methods that are currently in use. **DOI: 10.1061/(ASCE)SU.1943-5428.0000375.** *© 2021 American Society of Civil Engineers.*

Author keywords: Control network; Dam deformation; Optimization; Reciprocal reading; Slope distance reduction; Vertical refraction.

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BY MOHAMMAD BAGHERBANDI, SWEDEN, AND MASOUD SHIRAZIAN, IRAN FEATURE

ESSENTIAL TOOLS FOR DEFORMATION AND ENVIRONMENTAL MONITORING

Geodetic Control Networks: Challenges and Solutions

What are the key challenges in establishing precise geodetic control networks? This is one of the most important tasks of geodesists and land surveyors, since geodetic control networks are essential for the deformation and environmental monitoring of dams, tunnels, high towers, landslides and bridges, among others. This article discusses the main challenges relating to vertical angles and provides some recommendations for how they can be overcome.

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Physical and Geometric Effects on the Classical Geodetic Observations in Small-Scale Control Networks

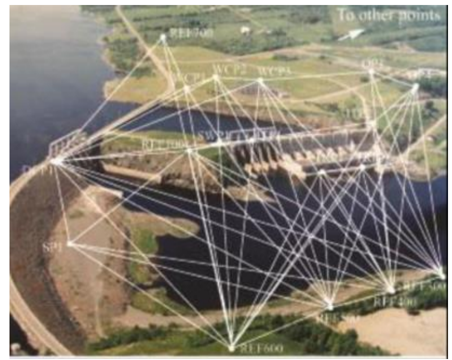
Mohammad Bagherbandi[1]; Masoud Shirazian[2]; Jonas Ågren[3]; and Milan Horemuz[4]

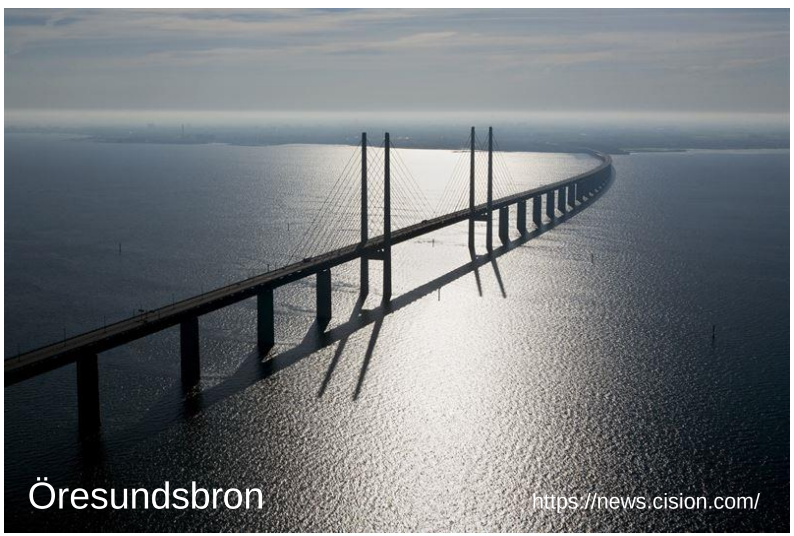
Abstract: In classical two-dimensional (2D) geodetic networks, reducing slope distances to horizontal ones is an important task for engineers. These horizontal distances along with horizontal directions are used in 2D geodetic adjustment. The common practice for this reduction is the use of vertical angles to reduce distances using trigonometric rules. However, one faces systematic effects when using vertical angles. These effects are mainly due to refraction, deflection of the vertical (DOV), and the geometric effect of the reference surface (sphere or ellipsoid). To mitigate refraction and DOV effects, one can choose to observe the vertical angles reciprocally if the baseline points' elevation difference is small. This paper quantifies these effects and proposes a proper solution to eliminate the effects in small-scale geodetic networks (where the longest distances are less than 5 km). The goal is to calculate slope distances into horizontal ones appropriately. For this purpose, we used the SWEN17_RH2000 quasigeoid model (in Sweden) to study the impact of the DOV applying different baseline lengths, azimuths, and vertical angles. Finally, we propose an approach to study the impact of the geometric effect on vertical angles. We illustrate that the DOV and the geometric effects on vertical angles measured reciprocally are significant if the height difference of the start point and endpoint in the baseline is large. Geometric correction should be considered for the measured vertical angles to calculate horizontal distances correctly if the network points are not on the same elevation, even if the vertical angles are measured reciprocally. **DOI: 10.1061/(ASCE)SU.1943-5428.0000407.**

Classical geodetic control network

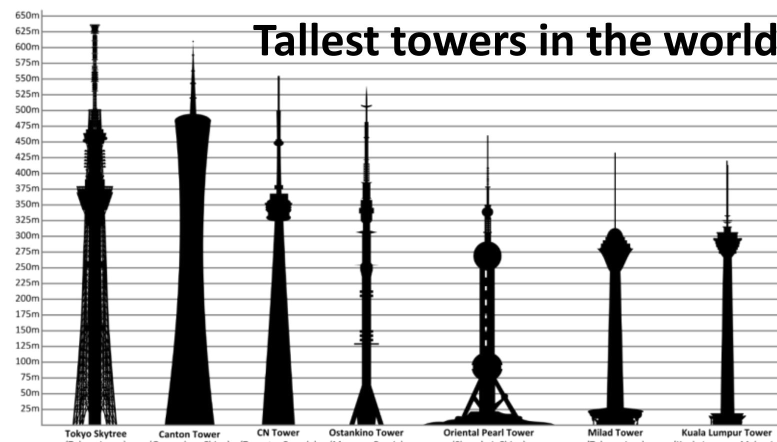
One of the primary issues of geodesy is the building and maintenance of small-scale precise geodetic control networks of which the longest baseline lengths are a few kilometers. e.g.

- To monitor the deformation or deflection in dams
- Bridges and Tunnels
- High towers
- Landslide





Tallest towers in the world Wikimedia



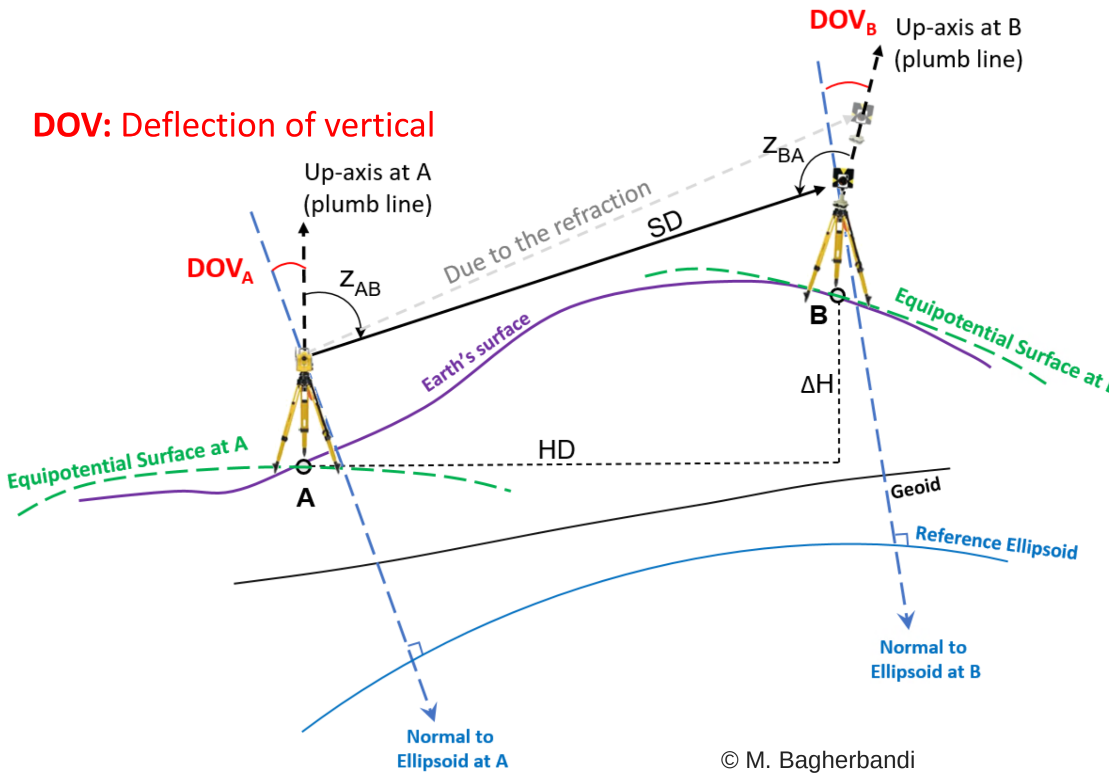
Reduction of slope distance to horizontal distance in the geodetic networks

Challenges

- Refraction error
- Geometric effects (Curvature-skewness)
- Physical effects (Deflection of the verticals)

Reducing slope to horizontal distances is a challenge for us (without involving any systematic error)

$$HD = SD\cos(90 - Z) = SD\sin Z$$



The **problem** is that we collect the observations on **the Earth's surface** (physical shape of the Earth), but the **Earth's mathematical shape** (e.g. Ellipsoid) is used for calculations.

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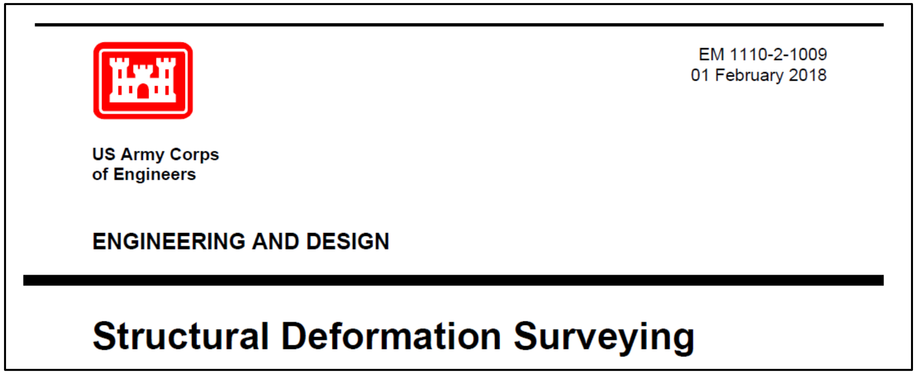
Aim

To quantify the physical and geometric effects (assuming a **spherical** and **ellipsoidal** Earth model) on the vertical angles by performing a simulation that can be relevant and useful for the writing of surveying guidelines.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These problems have not been mentioned in the guidelines.

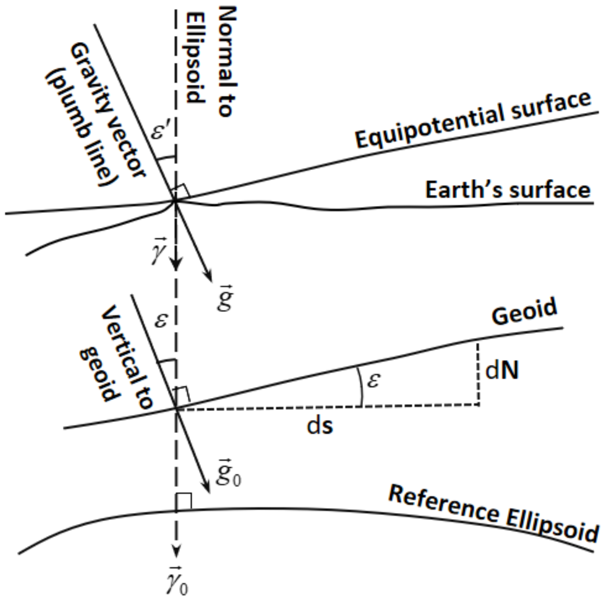
Deflection of vertical (DOV)

Physical error

- The DOV components at the Earth's surface using the quasigeoid and Molodenskij's definition of the height anomaly. Molodensky et al. (1962) discarded the geoid and defined a new surface, the quasigeoid, in which the geoidal undulation is replaced by height anomaly (Heiskanen and Moritz 1967, p. 312):

North-south component $$\xi' = -\frac{1}{R}\frac{\partial \varsigma}{\partial \varphi} - \frac{\Delta g}{\gamma}\frac{1}{R}\frac{\partial H}{\partial \varphi}$$

East-west component $$\eta' = -\frac{1}{R\cos\varphi}\frac{\partial \varsigma}{\partial \lambda} - \frac{\Delta g}{\gamma}\frac{1}{R\cos\varphi}\frac{\partial H}{\partial \lambda}$$



Data:

- SWEN17_RH2000 → is a geoid model
- The terrain inclinations are derived using the Swedish photogrammetric DEM (second terms).

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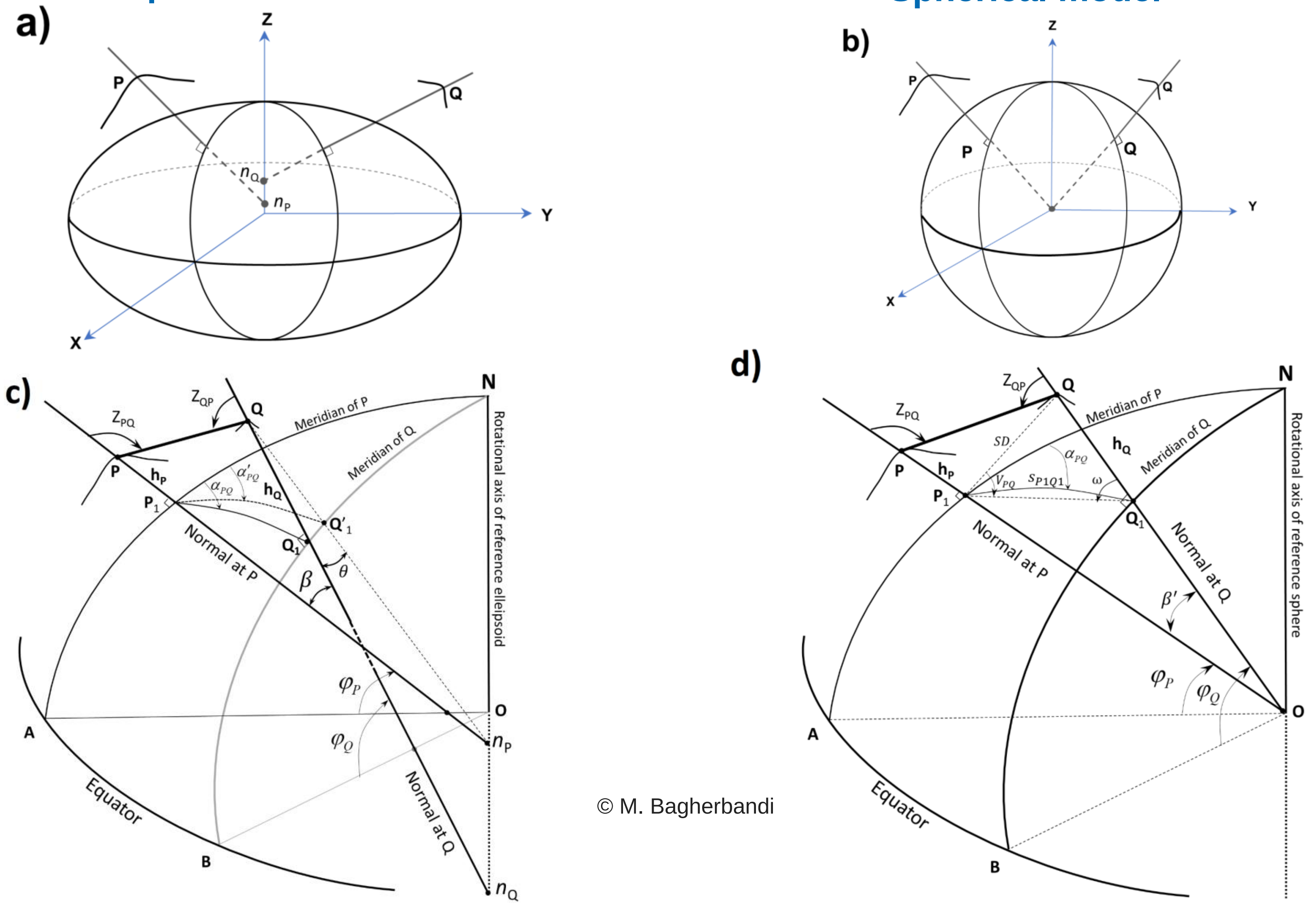
Curvature-skewness problem using ellipsoidal and spherical model

Geometric error

Ellipsoidal model

Spherical model



Curvature-skewness problem

Curvature problem

Solutions for the challenges

- **Challenges**
  - Refraction error,
  - Geometric effects (curvature-skewness)
  - Physical effects (Deflection of the verticals→ DOV)

- **Solutions:**
  - **Refraction error**: the recommended solution to solve this problem is the reciprocal reading of vertical angles at the same time from both ends of a distance

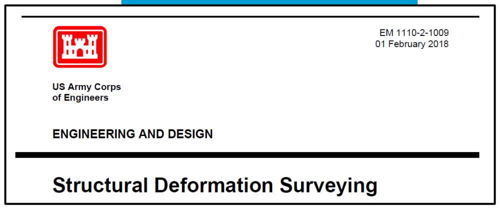
Vertical angles can be included in the calculations without any problem

  - **Solution 1:** Reciprocal reading can be a solution for **geometric** and **physical** effects, if the points are **at the same elevation**. Otherwise:
    - Curvature-skewness error should be taken into account for correcting vertical angles.
    - The DOV affects the collected zenith angles and should be used for converting slope distances to horizontal distances.
      - Using regional gravity database and calculating precise DOV components (i.e. ζ, η) and correcting the geodetic observations.

Collectling the vertical angles can be ignored

  - **Solution 2**: Terrestrial 3D geodetic control network (see HMK – Stommätning 2021 Section 3.2.4) and using only horizontal directions and slope distances.
  - **Solution 3**: Network-aided method (J. Surv. Eng., 2021, 147(4): 04021024).

HMK
– handbok i mät- och kartfrågor
Stommätning
2021



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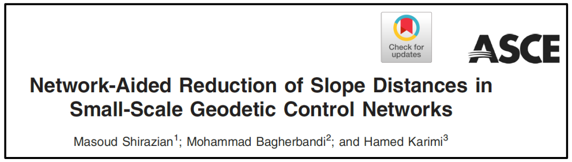

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Network-Aided Reduction of Slope Distances in Small-Scale Geodetic Control Networks
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Collecting reciprocal observations is **time-consuming**, especially in the rough topography areas (e.g. dam sites) and increases the fieldwork and costs of the projects. **Cost and time** are important factors to establish optimum and precise geodetic networks (Kuang 1996).

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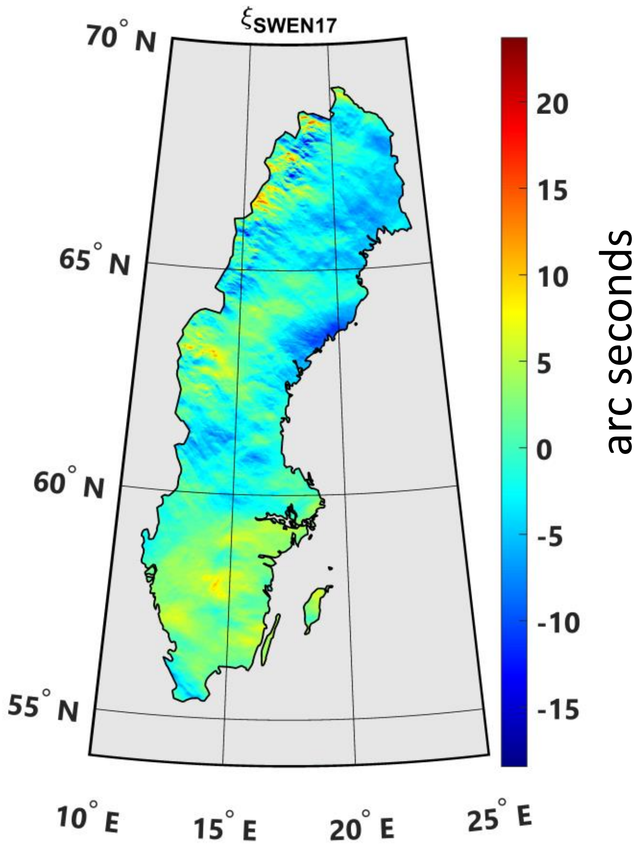
Quantifying physical (DOV) and Curvature-skewness errors on the reduction of slope distance to horizontal distance

Results: DOV components at the Earth's surface

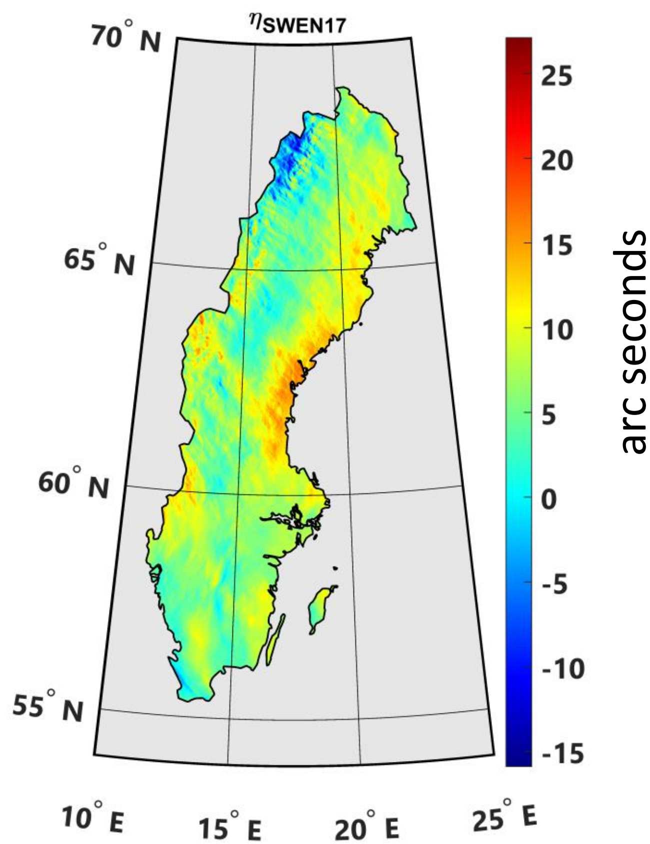
North-south component

$$\xi' = -\frac{1}{R}\frac{\partial\varsigma}{\partial\varphi} - \frac{\Delta g}{\gamma}\frac{1}{R}\frac{\partial H}{\partial\varphi}$$



East-west component

$$\eta' = -\frac{1}{R\cos\varphi}\frac{\partial\varsigma}{\partial\lambda} - \frac{\Delta g}{\gamma}\frac{1}{R\cos\varphi}\frac{\partial H}{\partial\lambda}$$



The resolution of the DOV components in latitude and longitude directions are 0.01° and 0.02°

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Effect of DOV on horizontal distances

- Effect of DOV on zenith angle

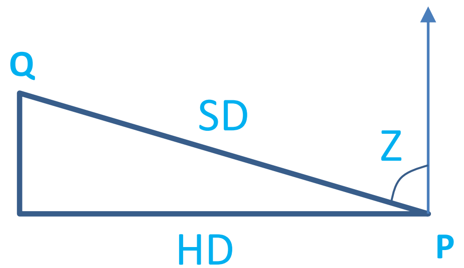
$$\delta_{Z_P} = \xi'_P \cos(\alpha_{PQ}) + \eta'_P \sin(\alpha_{PQ})$$

α: Azimuth

- Coverting slope distance to horizontal distance

$$HD = SD\cos(90 - Z) = SD\sin Z$$

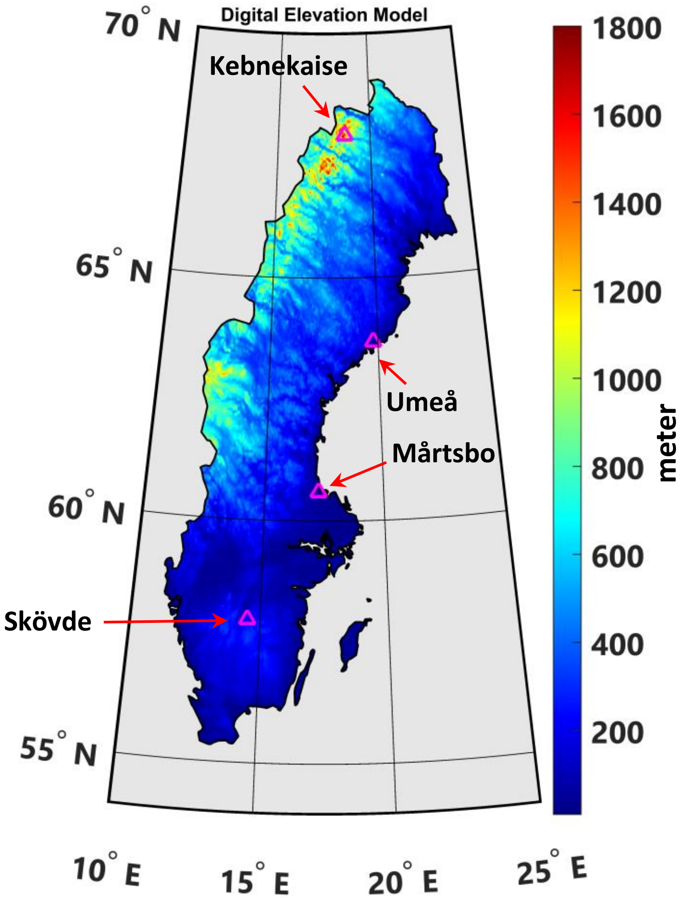
  - HD: horizontal distance
  - SD: Slope distance
  - Z: Zenith (vertical) angle



- Variation of HD due to the effect of DOV on Zenith angle:

$$\delta_{HD} = SD\ \sin(Z + \delta_{Z_P}) - SD\ \sin(Z)$$

Location	Latitude	Longitude	Height (m)
Kebnekaise	67.93° N	18.60° E	1702.3
Umeå	63.68° N	19.78° E	84.0
Mårtsbo	60.595143° N	17.258525° E	32.1
Skövde	57.95° N	14.50° E	262



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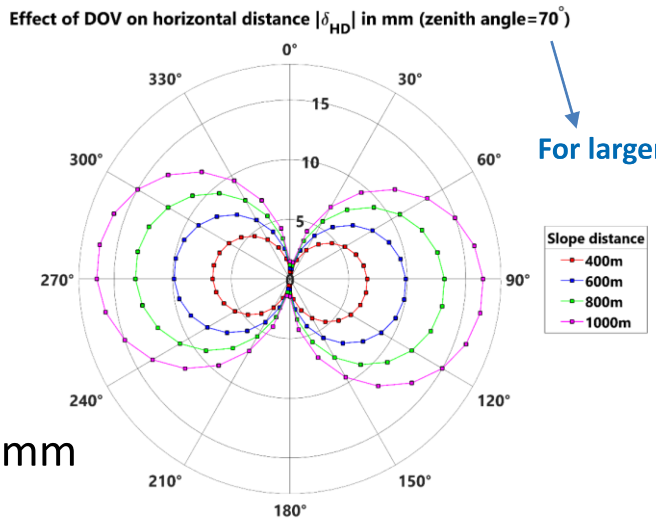
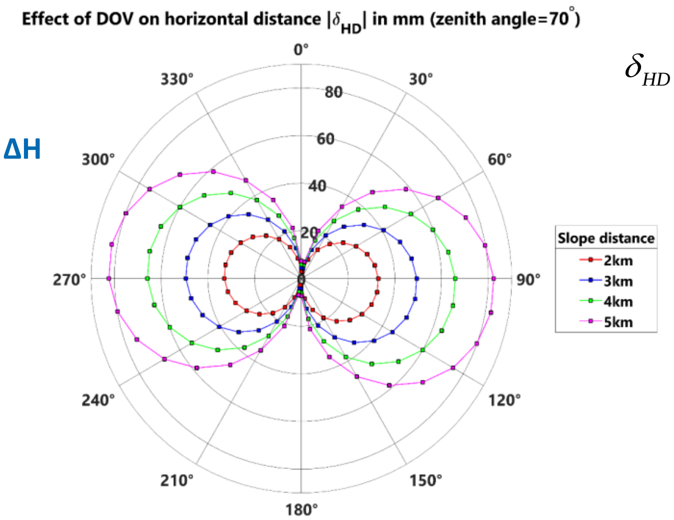
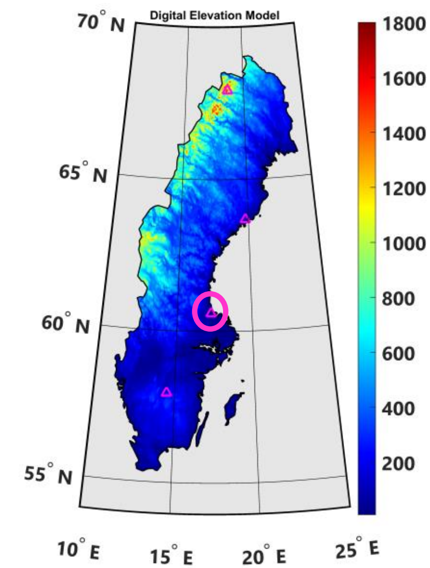
Effect of DOV on horizontal distances: Mårtsbo



For larger ΔH

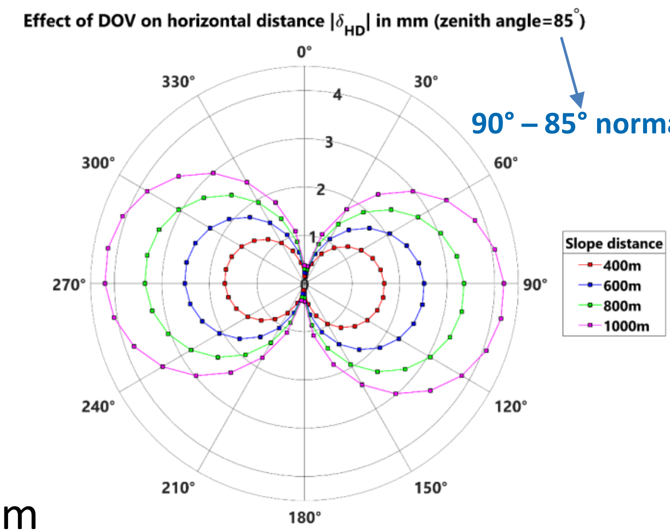


$$\delta_{HD} = SD\ \sin(Z + \delta_{Z_P}) - SD\ \sin(Z)$$

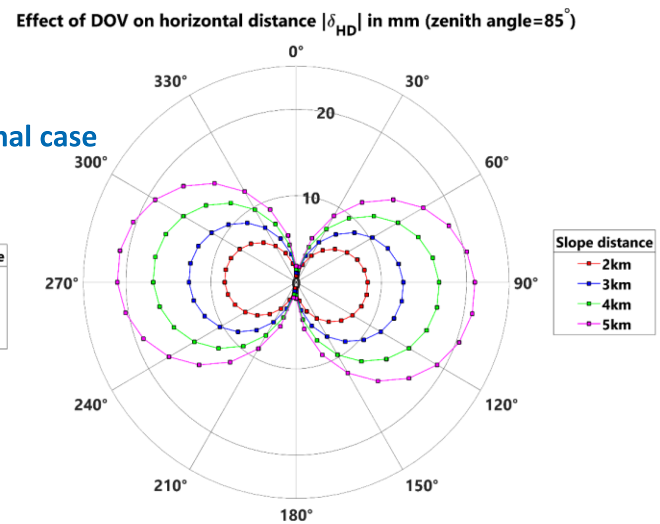


1 km

16.5 mm



90° – 85° normal case



1 km

4.2 mm

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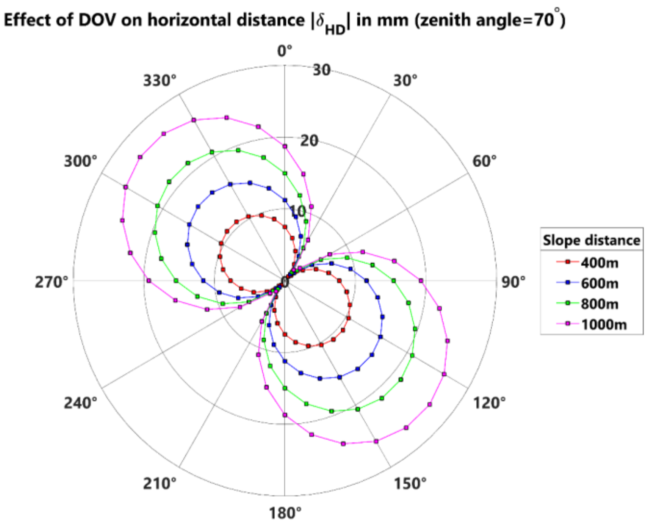
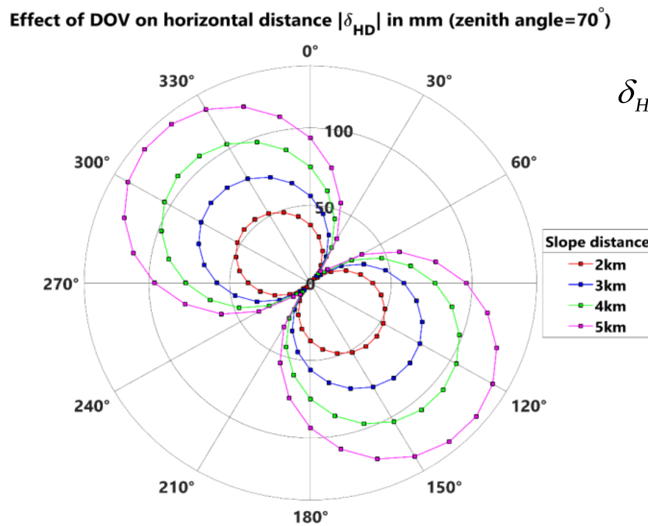
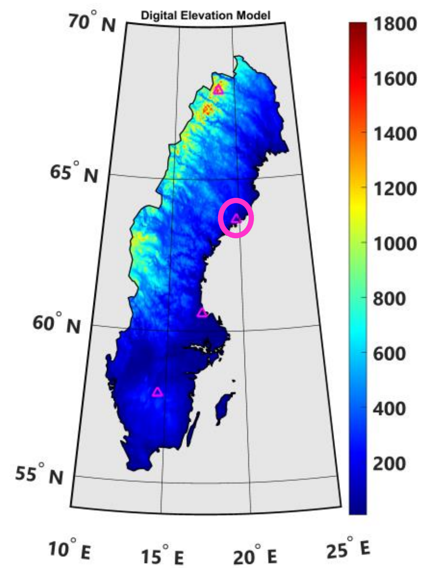
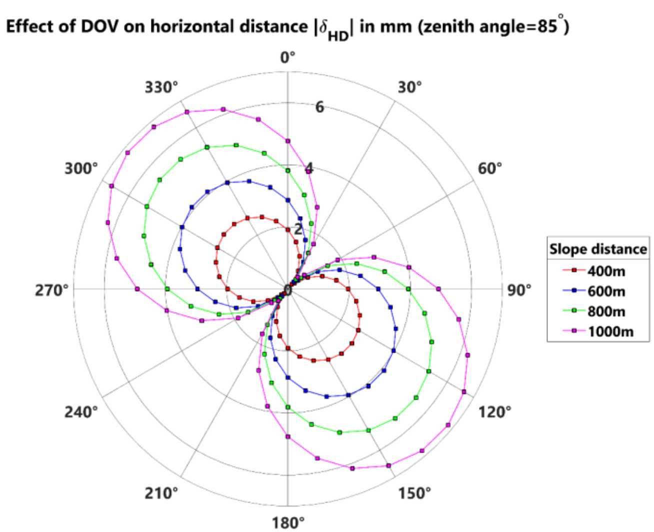
Effect of DOV on horizontal distances: Umeå

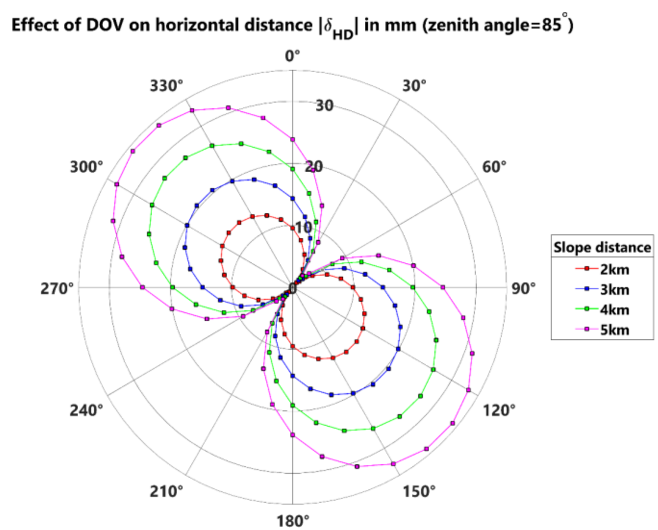




$$\delta_{HD} = SD\ \sin(Z + \delta_{Z_P}) - SD\ \sin(Z)$$







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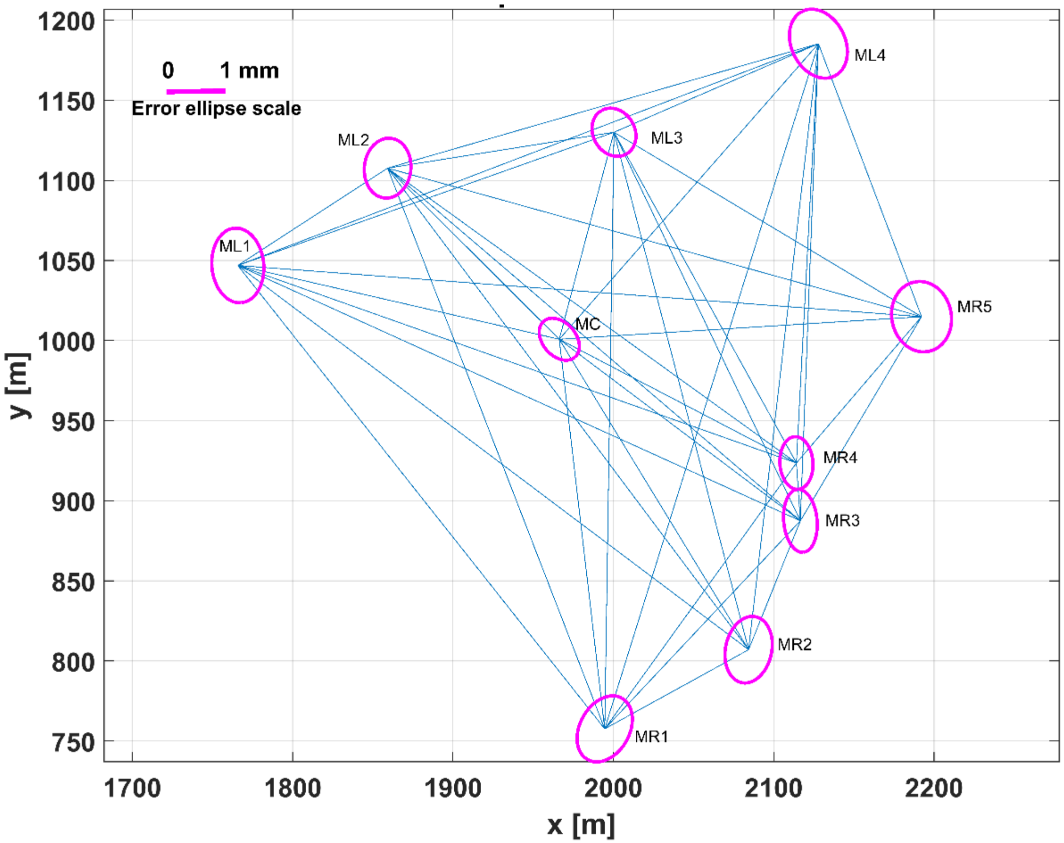
Effect of DOV on horizontal distances

The DOV effect depends on

- Baseline length
- Height difference
- **Azimuth**

The effect of DOV (physical effect) will not be **uniform** in the network because of the baselines' **different azimuths**.



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Geometric problem

How to calculate the curvature-skewness effect on slope distance reduction?

Curvature problem using spherical model

- The angle between two normals (at points P and Q) can be obtained by

$$\beta' = \frac{s_{P_1Q_1}}{R_m}$$

- To simplify the simulation, one can assume that the first point (i.e. P) is projected on the sphere surface h_p=0, thus the slope distance between points P1 and Q is given by:

$$SD = \sqrt{R_m^2 + (R_m + h_Q)^2 - 2R_m(R_m + h_Q)\cos\beta'}$$

- The slope angle on the sphere at point P1

$$V_{P_1Q}^{spherical} = arc\sin\left(\frac{h_Q \sin\omega}{SD}\right)$$

$$\omega = (\pi + \beta')/2$$

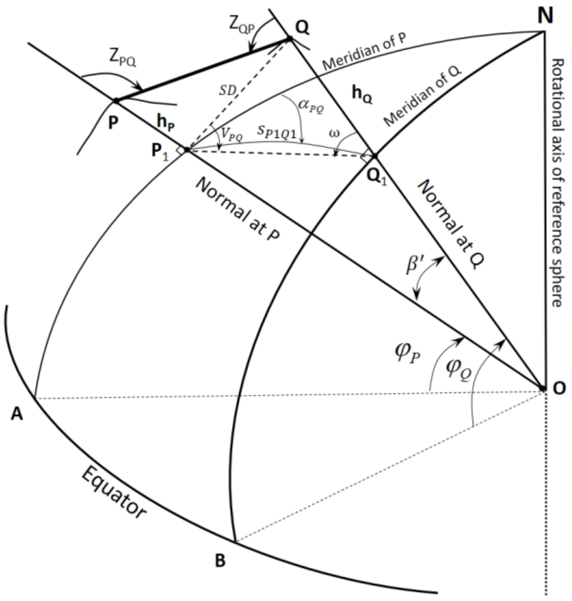
- The curvature error on the slope distance reduction (reciprocal reading)

$$V_{PQ} = V = 90 - Z$$

$$V_{QP} = -V - \beta'$$

$$\bar{V} = \frac{1}{2}\left(V_{PQ} - V_{QP}\right) = V + \frac{\beta'}{2}$$

$$\delta_{HD}^{Curvature} = SD\ \cos\left(V_{P_1Q}^{spherical} + \frac{\beta'}{2}\right) - SD\ \cos\left(V_{P_1Q}^{spherical}\right)$$



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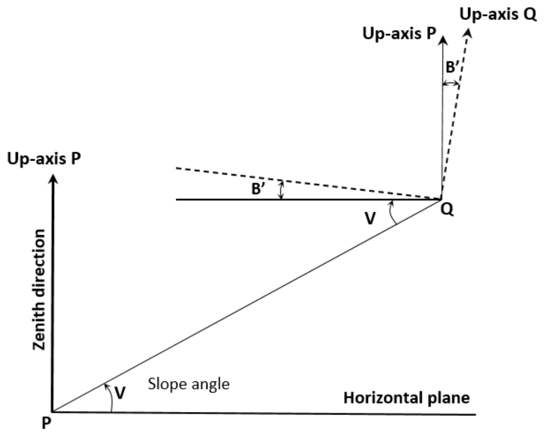
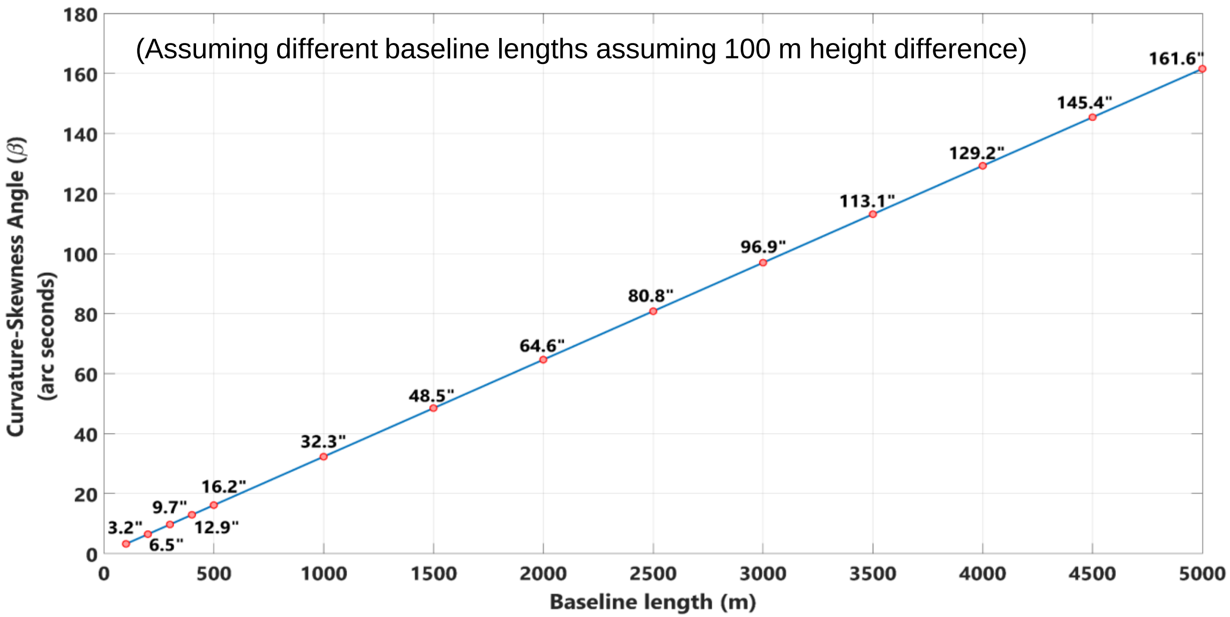
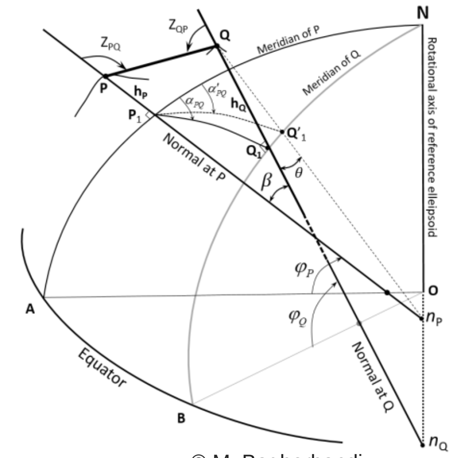


Angle between normals (curvature-skewness angle)





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Sectional view of normal skewness at points P and Q above an ellipsoid of revolution.

Height difference (meter)	Distances (meter)										
	100	300	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.4
5	0.0	0.1	0.2	0.4	0.6	0.8	1.0	1.1	1.3	1.4	1.5	1.6
10	0.1	0.2	0.4	0.8	1.2	1.5	1.9	2.3	2.6	2.9	3.2	3.5
50	0.4	1.2	1.9	3.9	5.9	7.8	9.4	11.7	13.6	15.5	17.3	19.2
100	0.8	2.4	**3.9**	7.8	11.7	15.6	19.5	23.4	27.3	31.1	34.9	38.8
150	1.2	3.5	5.9	11.8	17.6	23.5	29.3	35.2	41.0	46.8	52.6	58.4
200	1.6	4.7	7.8	15.7	23.5	31.3	39.1	46.9	54.7	62.5	70.2	77.9
250	2.0	5.9	9.8	19.5	29.4	39.1	48.9	58.7	68.4	78.1	87.8	97.5
300	---	---	11.7	23.5	35.2	47.0	58.7	70.4	82.1	93.8	105.5	117.1
400	---	---	15.7	31.3	47.0	62.6	78.3	93.9	109.5	125.1	140.7	156.3
500	---	---	19.6	39.2	58.7	78.3	97.9	117.4	136.9	156.4	175.9	195.4

The curvature-skewness effect on the slope distance reduction in reciprocal measurements.
Unit: mm

The curvature-skewness effect depends on

Baseline length

Height difference

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Teknisk specifikation
SIS-TS 21143:2016

SWEDISH STANDARDS INSTITUTE

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Språk/Language: svenska/Swedish
ICS: 91.200

Byggmätning – Geodetisk mätning, beräkning och redovisning av byggnadsverk och infrastruktur

Engineering survey for construction works – Surveying and mapping on edifice and infrastructure

Tabell 1 – Totalstationer

Klass	Användningsområden	Medelfel i riktning (1 helsats)	Medelfel i vertikalvinkel (1 helsats)	Medelfel i längd
T1	Stommätning för industritillämpning och rörelsekontroller. Kontrollmätning av byggnadsverk med särskilt höga krav.	0,2 mgon	0,2 mgon	1 mm + 2 ppm
T2	Stommätning för väg- och järnvägsprojekt. Detalj- och kontrollmätning av spåran-läggning, bro- och tunnelkonstruktioner, hus- och industribyggnader o d	0,6 mgon	0,6 mgon	3 mm + 3 ppm
T3	Övrig stommätning. Detaljmätning för väg och övriga byggnadsverk samt detaljmät-ning inom planlagt område. Kontrollmät-ning av övriga anläggningar.	1 mgon	1 mgon	3 mm + 3 ppm
T4	Övrig detaljmätning.	2 mgon	2 mgon	5 mm + 5 ppm

ANM.1 Totalstation med automatisk inriktning mot prisma anges med tillägg till klass enligt tabell 2.

ANM.2 Mätutrustningars noggrannhet anges som medelfel. Medelfelen i tabellen kan direkt jämföras mot standardavvikelser baserade på DIN 18723, förutom den avståndsberoende delen (ppm-delen) för medelfel i längd, som inte ingår i den tyska standarden. Med ppm avses parts per million dvs. mm/km.

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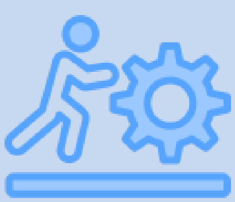
Is it possible to avoid reading vertical angle and get rid of the challenges?

Refraction error
Geometric effects (Curvature-skewness)
Physical effects (Deflection of the verticals)

Our suggestions:



Solution 1: Reciprocal reading can be a solution for **geometric** and **physical** effects, if the points are **at the same elevation.**
Solution 2: Terrestrial 3D geodetic control network (see HMK – Stommätning 2021 Section 3.2.4) and using only horizontal directions and slope distances.

Solution 3: Network-aided method (J. Surv. Eng., 2021, 147(4): 04021024).

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Network-Aided Reduction of Slope Distances in Small-Scale Geodetic Control Networks

Masoud Shirazian[1]; Mohammad Bagherbandi[2]; and Hamed Karimi[3]

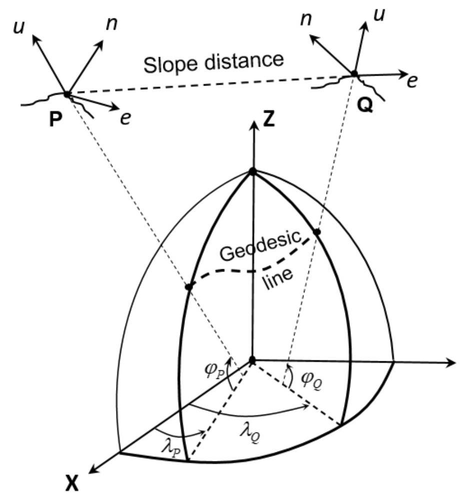
Journal of Surveying Eng., 2021, 147(4): 04021024

- Adjusting the slope distance observations (**unidirectional**) in the form of a 3D free network adjustment

- Computing adjusted coordinates (e n u) for all network points using the initial values of coordinates of the geodetic control points

- Computing horizontal distances $D_{ij} = \sqrt{(\hat{e}_i - e_j)^2 + (n_i - n_j)^2}$

- The calculated horizontal distances, along with the horizontal angles or direction observations, are used then in the process of the 2D network in the final free network adjustment



Is it possible to avoid reading vertical angles?
Answer: YES!

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Network-Aided Reduction of Slope Distances in Small-Scale Geodetic Control Networks

Damghan reservoir rockfill dam

Mojen reservoir rockfill dam

Table 1. Specifications of the dams of the study areas

Marker on the map	Name	Dam type	Date of construction	Length (m)	Height (m)
A	Mojen	Rock fill	2018	276	49
B	Damghan	Rock fill	2005	445	54.5

Table 2. The data specifications of every observation set

Dam name	Epoch	Date of observation	Instrument used	Distance STD	Horizontal angle STD	Vertical angle STD
Damghan	Epoch no. 2	03/2010	WILD TCA2003	1 mm + 1 ppm	0.5"	0.5"
Mojen	Epoch no. 1	10/2018	WILD T2000 & DI2002	1 mm + 1 ppm	0.5"	0.5"

Note: STD = standard deviation.

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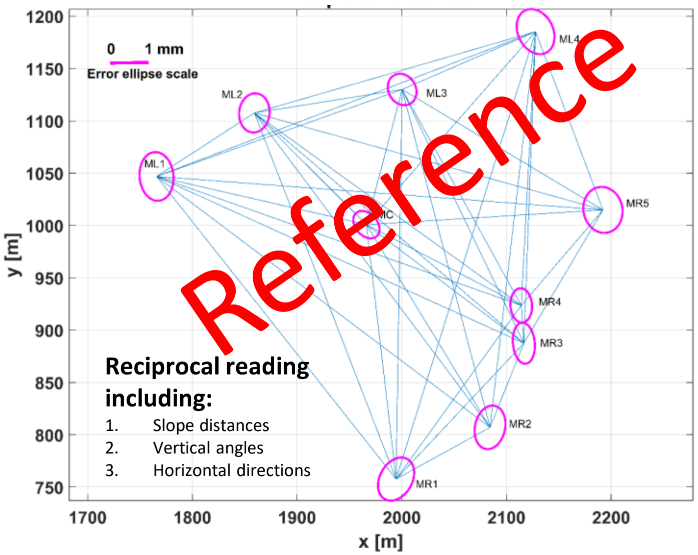
Reciprocal vs unidirectional (network aided) slope distances: Mojen dam

Reciprocal observations



Unidirectional observations (Network-aided method)

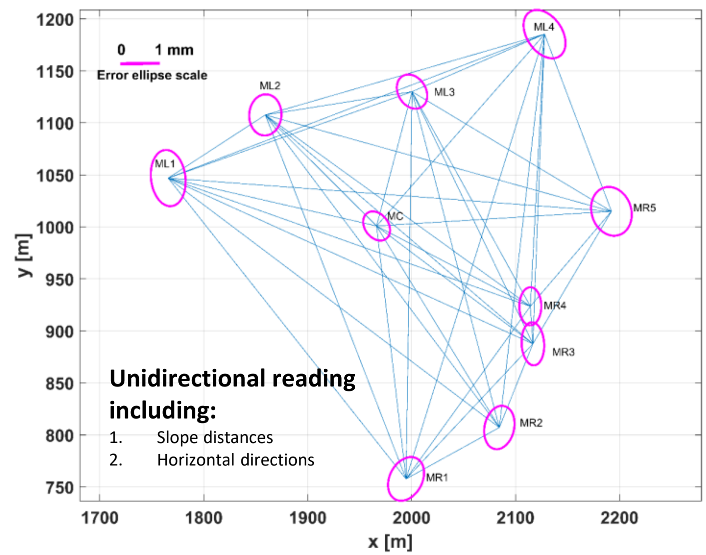


Table 4. Comparison of error ellipses and coordinate differences using reciprocal slope distances and unidirectional slope distances in Mojen dam's geodetic control network

	Using reciprocal slope distances			Using unidirectional slope distances			Difference between coordinates	
Station ID	95% semimajor axis (mm)	95% semiminor axis (mm)	Azimuth of major axis (degrees)	95% semimajor axis (mm)	95% semiminor axis (mm)	Azimuth of major axis (degrees)	Δx (mm)	Δy (mm)
ML1	0.7	0.5	354.7213	0.9	0.5	353.0683	0.2	0.1
ML2	0.6	0.5	6.127042	0.6	0.5	3.861579	0.2	0.3
ML3	0.5	0.4	330.1408	0.6	0.4	328.1169	0.2	0.2
ML4	0.7	0.5	333.4098	0.8	0.5	325.4762	0.6	0.2
MR1	0.7	0.5	29.12523	0.7	0.5	27.69237	0.1	0.2
MR2	0.7	0.5	12.04362	0.7	0.4	12.61253	0.0	0.1
MR3	0.6	0.3	354.7195	0.7	0.3	356.5797	0.3	0.4
MR4	0.5	0.3	356.3522	0.6	0.3	0.426271	0.3	0.5
MR5	0.7	0.6	348.3158	0.8	0.6	342.0895	0.2	0.1
MC	0.5	0.3	318.8208	0.5	0.4	322.8739	0.0	0.1

Note: ID = identification.

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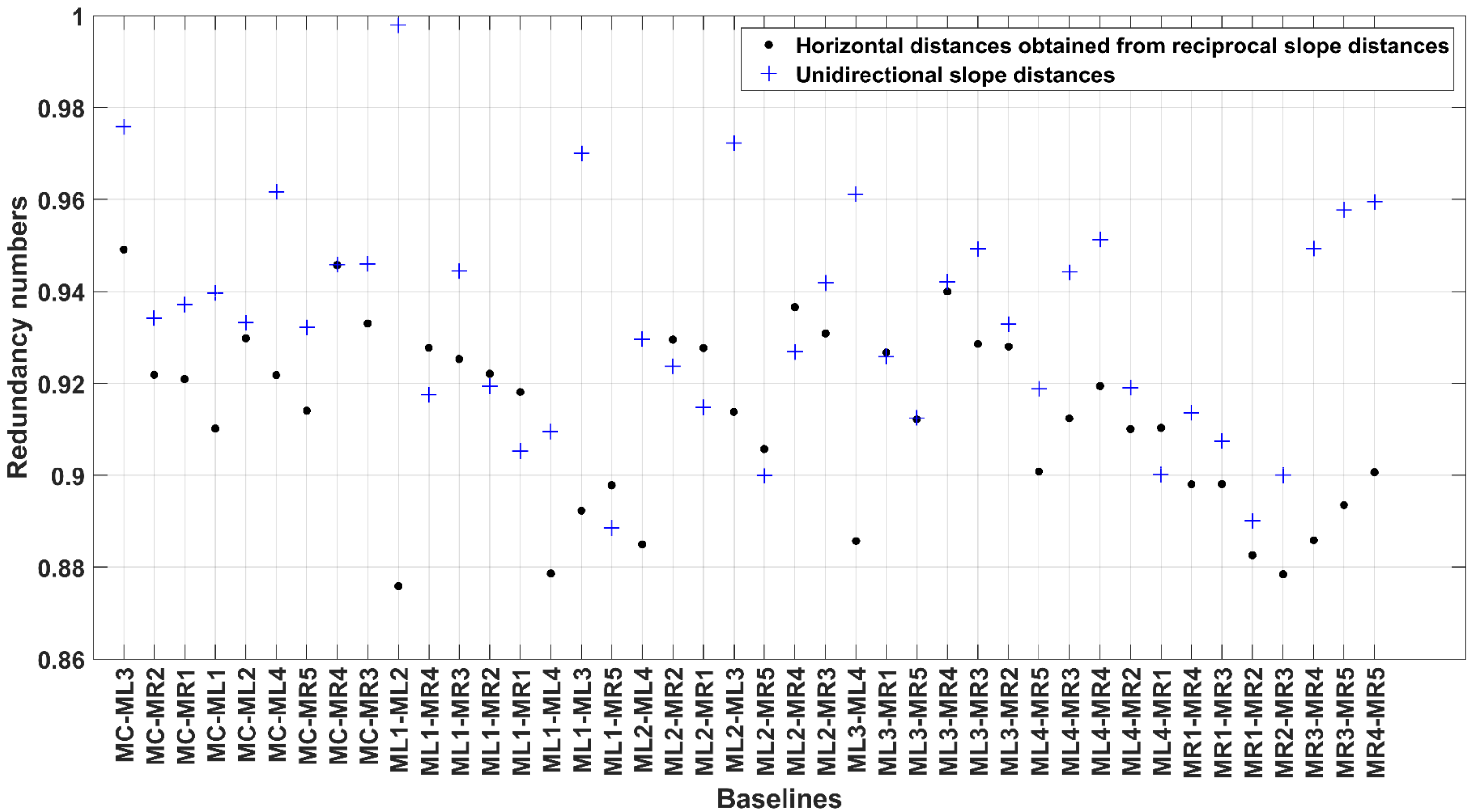
Reciprocal vs unidirectional (network aided) slope distances: Mojen dam



- The redundancy numbers reflect the geometrical strength of a geodetic network.
- It is desirable to design a network with relatively large (close to 1) and uniform redundancy numbers.
- The redundancy numbers show the ability to detect gross errors in the network.

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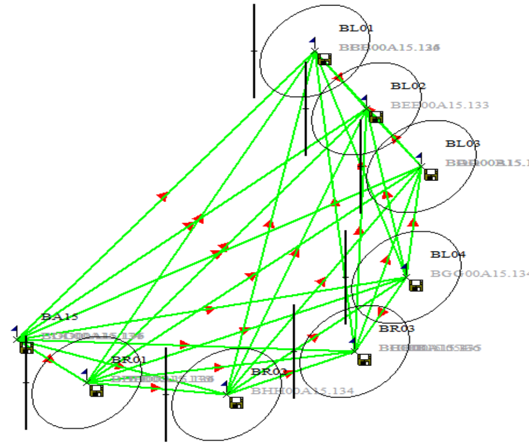
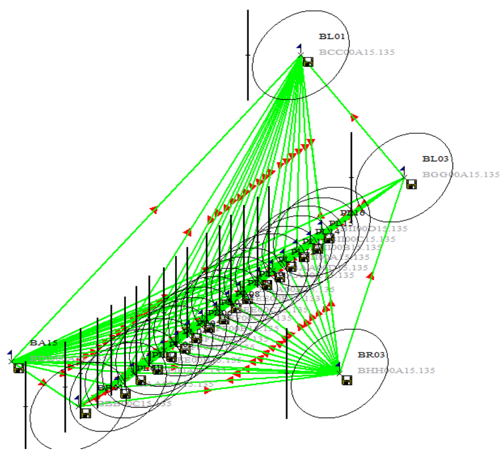
Take home messages

- The physical and geometric impacts on the vertical angle are important to convert the slope distances to the horizontal ones in the geodetic networks
- One practical solution (according to the surveying guidelines) to eliminate these problems is collecting the vertical angles **reciprocally** and designing the geodetic networks so that the stations' elevations are as much at the **same level** as possible.
  - following the guidelines is sometimes difficult because of the project circumstances
    - establishing a geodetic network for monitoring high towers and structures,
    - existing rough topography.
  - Therefore, designing a geodetic network with all stations **at the same elevation is not always possible**
  - Our results show that ignoring these effects may lead to significant errors, especially if the height differences between the points are large,
    - Even if one measures the vertical angles reciprocally

Off-dam network



On-dam network



Solution:

Network-aided method

Take home messages

Thank you for your attention!

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