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Kingdom of Saudi Arabia
General Commission for Survey

Refraction coefficient determination and modelling for the territory of the Kingdom of Saudi Arabia

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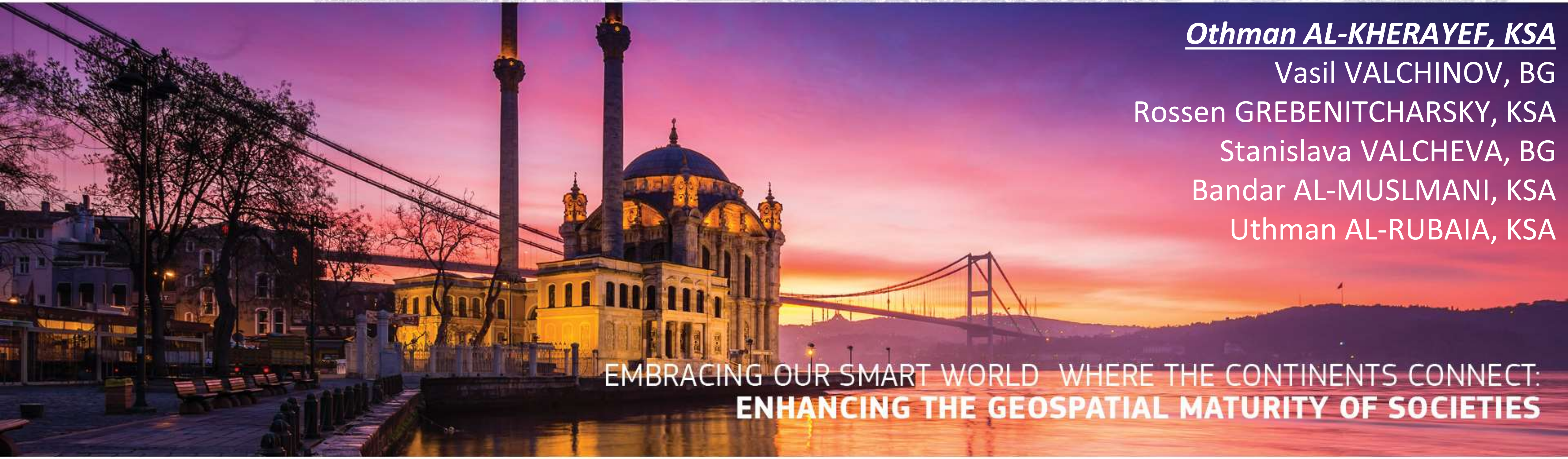

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Introduction

- Precise levelling is essential for establishing a National Vertical Reference System (NVRS);
- Refraction affects precise levelling by increasing the loop misclosures; refraction effect on measured height difference per setup could reach up to 1-2 mm;
- Levelling instrument's software automatically correct for refraction using standard atmospheric-pressure models;
- The real influence of refraction on the line of sight depends on the topography roughness along the levelling line and the air temperature

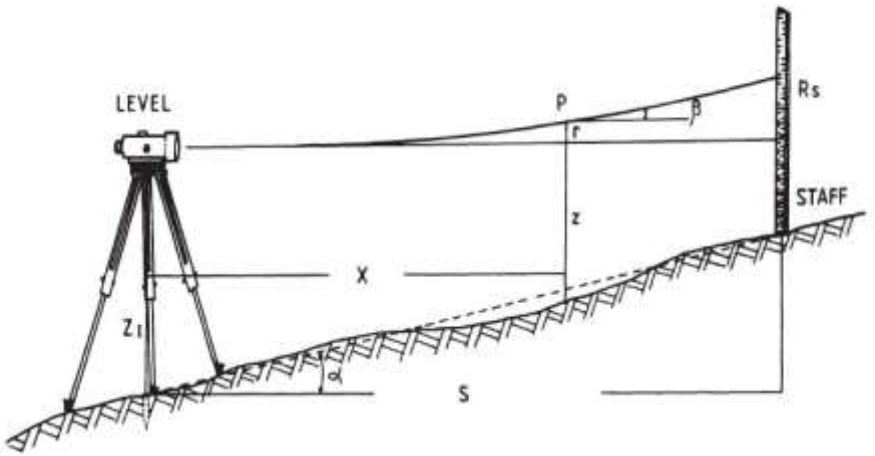


Figure 1. Derivation of Refraction Correction R_S

(Angus-Leppan, 1984)

If temperature observations obtained during levelling are available, the refraction effect could be modelled -> improve the accuracy of the levelling networks

Aim

The aim: to present results from the **Refraction Coefficient Determination for Precise Levelling Observation (RCD_PLO)** project closely linked to the establishment of a new National Vertical Reference Frame for the KSA

The focus:

1) computation and modelling of refraction for precise geodetic levelling using the available temperature triplets collected during the precise levelling;

2) accounting for topography roughness along the line of sight by employing the so-called 'equivalent height'.

Problem background and methodology

Kukkamaki's formula for refraction correction to rod reading:

$$R_i = \left(ctg^2\theta\right) d \, \frac{\Delta t}{z_2^C - z_1^C} \left(\frac{1}{C+1} Z_i^{C+1} - Z_0^C Z_i + \frac{C}{C+1} Z_0^{C+1} \right)$$

with **theoretical** refraction coefficient: ***C = -1/3***

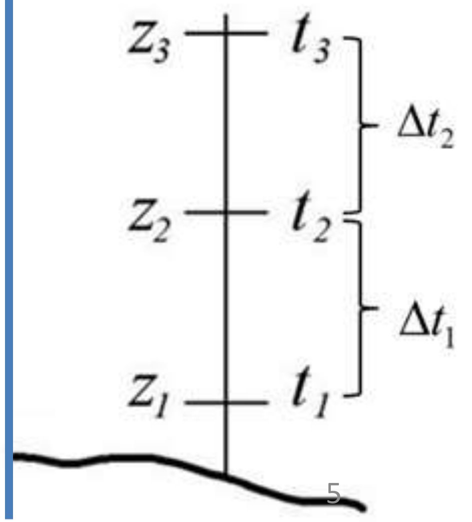
with classical formula refraction coef.: $C = \ln\left(\frac{t_3 - t_2}{t_2 - t_1}\right) \Big/ \ln\left(\frac{z_2}{z_1}\right)$

with **modified refraction coefficient:** $C = \ln\left(\frac{\Delta t_2}{\Delta t_1}\right) \Big/ \ln(3) \quad but \; \frac{2.5}{1.5} \neq \frac{1.5}{0.5}$

assuming:

$$\frac{z_2}{z_1} = \frac{z_3}{z_2},$$

where



Problem background and methodology

Kukkamaki’s formula for refraction correction to rod reading:

$$R_i = \left(ctg^2\theta\right) d \, \frac{\Delta t}{z_2^C - z_1^C} \left(\frac{1}{C+1} Z_i^{C+1} - Z_0^C Z_i + \frac{C}{C+1} Z_0^{C+1} \right)$$

Utilizing:

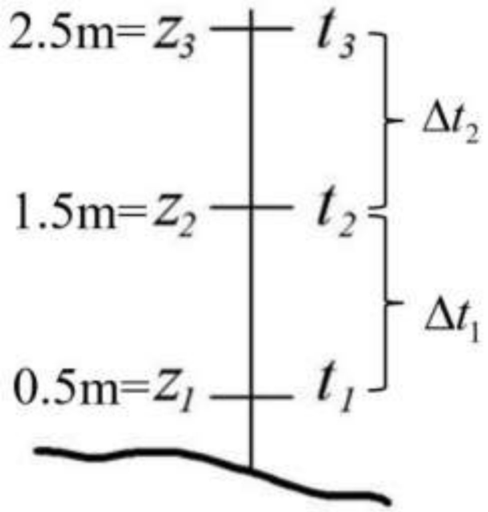
$$\begin{cases} t_1 = a + b z_1^C \\ t_2 = a + b z_2^C \\ t_3 = a + b z_3^C \end{cases}$$

assuming $T = \frac{t_3 - t_2}{t_2 - t_1}$

New refraction coefficient formula:

$$C = 2 \frac{\ln\left[\frac{\left| T \pm \sqrt{T^2 + 4T} \right|}{2} \right]}{\ln 3}$$

assuming:

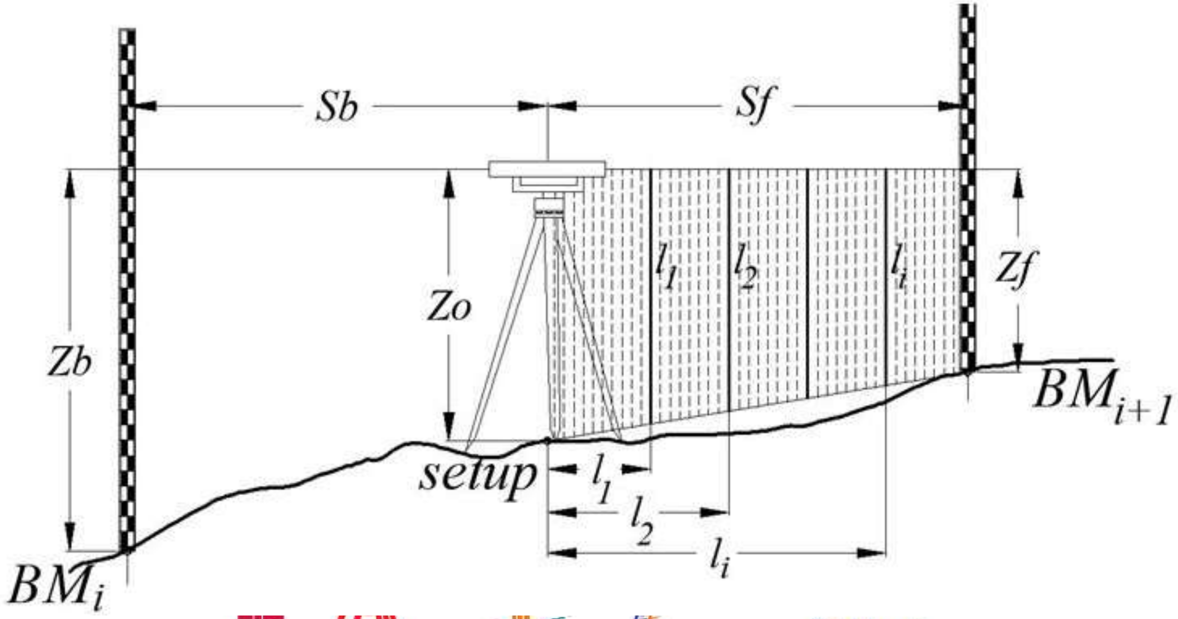


but the available t_i at z_i do not satisfy the condition

Problem background and methodology

Computing the equivalent height:

$$\frac{1}{h_e} = \frac{2}{S^2}\int_0^S \frac{l}{h}\,dl = \frac{2}{S^2}\sum_{i=0}^{S} \frac{l_i}{h_i}\,\frac{l_{i+1} - l_{i-1}}{2}$$



Refraction effect on the height difference is:

$$C_{ref} = \left(R_{back} - R_{for}\right)$$

Accounting for topography roughness:

$$C_{equiv} = C_{ref}\left(\frac{1}{h_{e\_back}} - \frac{1}{h_{e\_for}}\right)$$

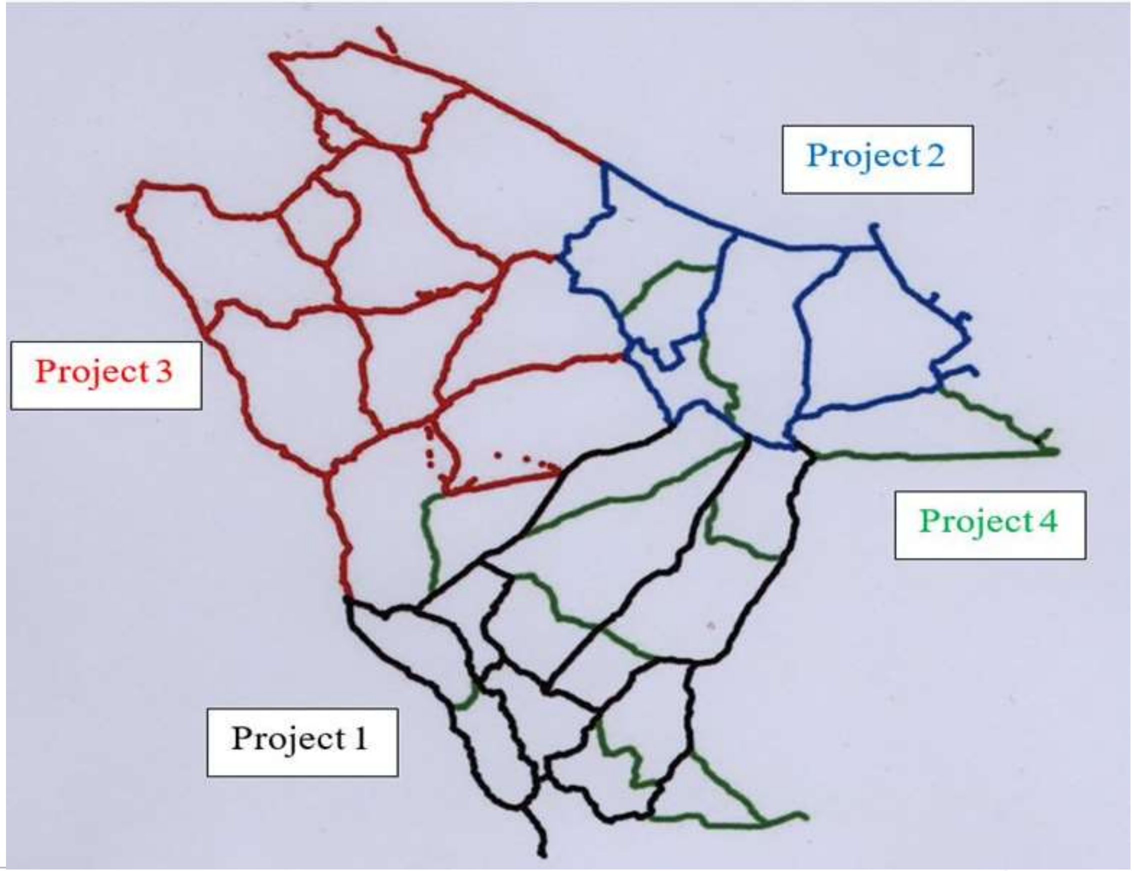
C_{ref} uses both modified classical and new formulae for refraction coefficient!

Field tests: NVN & available data

GCS is responsible for the establishment of National Vertical Network (NVN) for the KSA

Since 2010, GCS has carried out four phases of precise geodetic levelling: both in forward and backward direction

At most phases simultaneous measurements of temperature at 3 different reference levels above the ground



Field tests: NVN & available data

Amount of data to be processed: levelling: > 620 000; temperature: > 580 000

Pr. No	Elevation [m]		Temperature [°C]			Temperature reference level [m]			*C*-value used by the Contractors	Measurement period (month, year)
	Low	High	Low	High	Ave	z_1	z_2	z_3		
1	2	1600	6	47	25.6	0.3	1.3	---	-0.347	VI – VIII.12
						0.5	1.5	2.5		IX – III.13
2	1	783	3.1	47	24.8	0.3	1.3	---	-0.347	III – IX.12
						0.5	1.5	2.5		
3	3	1060	6	47	27.0	0.5	1.5	2.5	-0.347	IX.13 – III.14
4	2	2097	-0.7	46	29.5	0.5	1.5	2.5	-0.410	IX.15 – III.16

Field tests: software development

Functions of the different REFRACTION submodules

1. Convert	1. Converts s 2. Creates *_
1.1 Con_P12	Converts the and 2 into the
1.2 Con_P34	Converts the and 4 into th
2. Benchmarks	Reads the (B
3. Hight_Benchmarks	Computes the
4. HeightSetup	Computes the
5. Accuracy_C	1. Computes value for the 2. Performs s
6. Equivalent	3.1. Calculat 3.2. Comput section's *C*-v 3.3. Calculat correction is 3.4. Comput account 3.2 a
7. Difference	Computes di backward lev

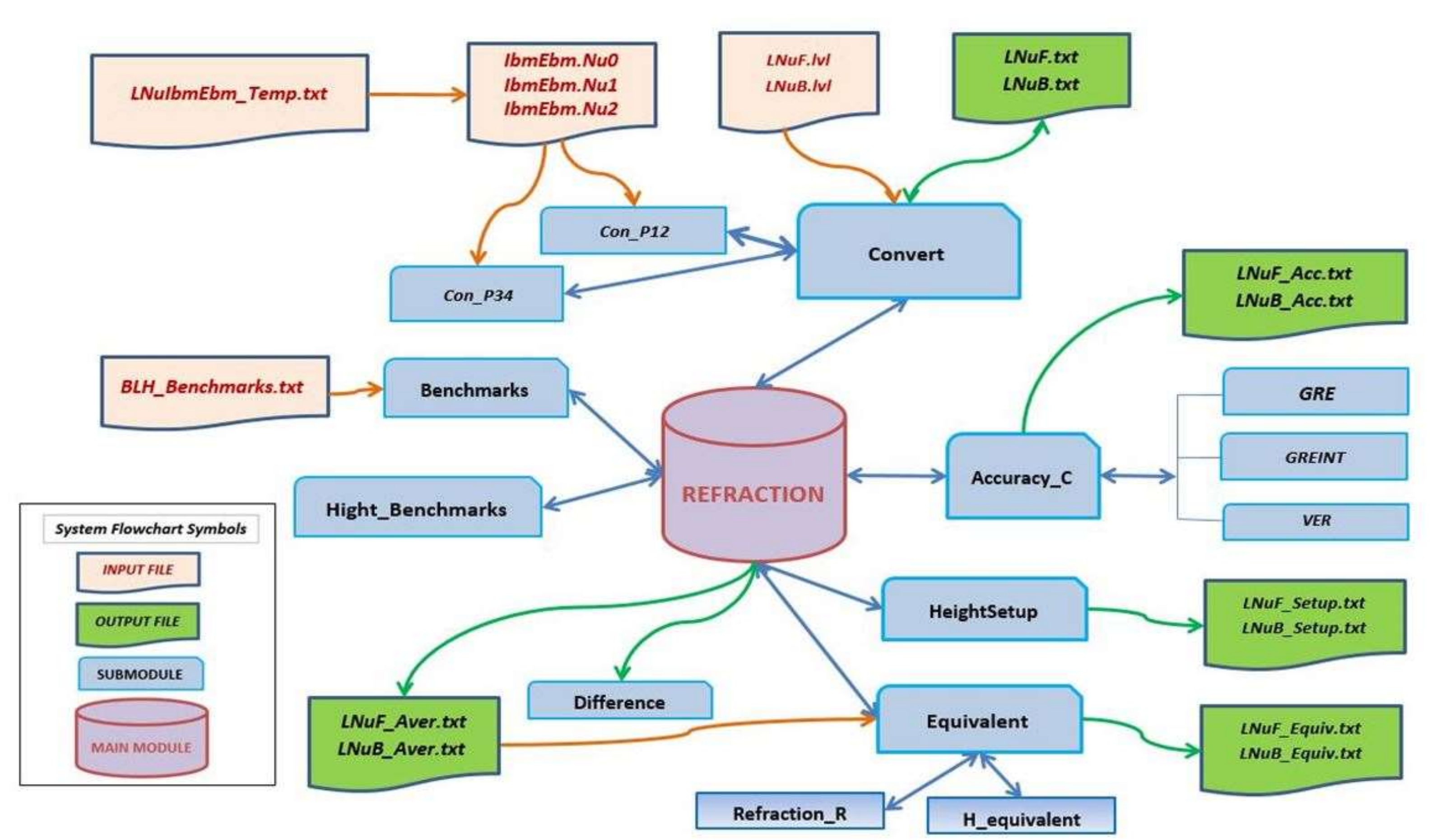


Figure 5: Flowchart of the REFRACTION package

```
N S
 backward               |        |
Nsec   C+   | C+aver| H_aver|
 66 0.506 |   0.482| 274.32|
 48 0.463 |   0.498|1157.85|
 36 0.443 |   0.407|  26.26|
  4 0.152 |   0.210| 164.42|
 32 0.441 |   0.418|1526.20|
 25 0.502 |   0.410|1027.15|
 51 0.390 |   0.408| 873.52|
 25 0.379 |   0.357| 645.22|
302 0.447     0.435
    0.056     0.028
N S
 backward               |        |
Nsec   C+   | C+aver| H_aver|
 76 0.447 |   0.443| 538.56|
 64 0.455 |   0.459|1176.64|
 24 0.403 |   0.409| 946.87|
 67 0.420 |   0.401|  19.46|
 39 0.313 |   0.300| 841.06|
 76 0.467 |   0.474|1580.89|
  8 0.133 |   0.158|1254.45|
 39 0.468 |   0.409|1019.68|
 96 0.404 |   0.437| 900.63|
 58 0.421 |   0.352| 614.61|
547 0.422     0.412
    0.053     0.031
... 2202
ent  399
ent  302
ent  624
ent  677
```

Field tests: computations & accuracy

Scenarios for refraction coefficient *C* computations

For each scenario two formulas were applied (the modified classical formula and the new one)

1) one average ***C***-value for the territory of the KSA

2) two types of ***C***-values per setup considering:

- ✓ case of normal atmosphere, where (***C***-values<0) – 54% of the computed ***C***-values
- ✓ case of inverse atmosphere, where (***C***-values>0) – 46% of the computed ***C***-values

3) average ***C***-value per section

4) ***C***-values referring to the middle point of the section (subjected to statistical testing)

5) average section ***C***-values from single/double runs (subjected to correlation analysis)

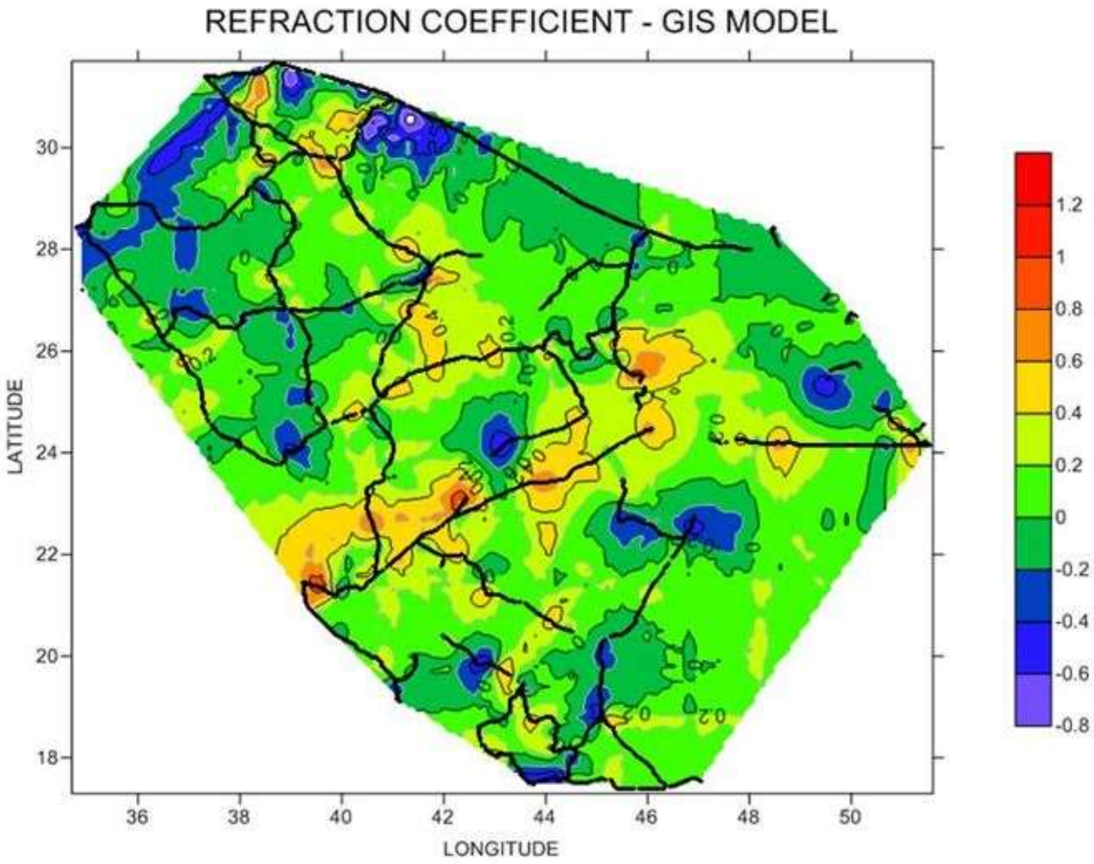
6) ***C***-values per levelling line sections as a moving average from section *C*-values;

All *C*-values in 5) and 6) are consistent; with STD of about 0.02;

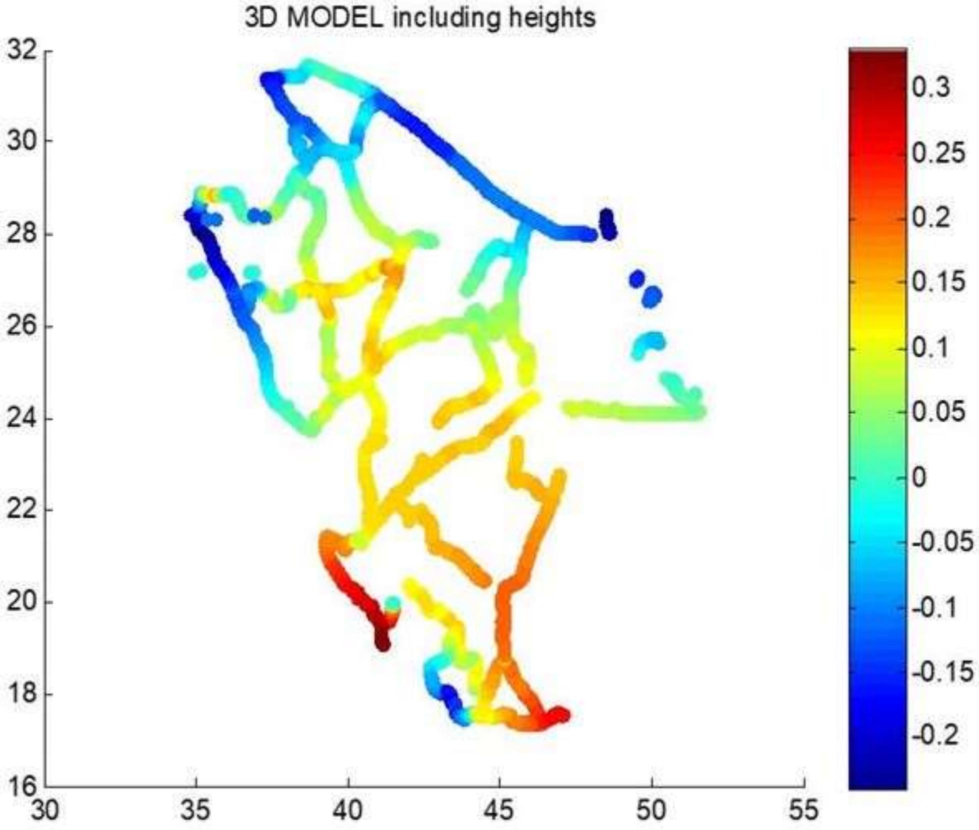
The C-values for forward and backword directions are coherent which shows the existence of a real signal In filtered C values

Field tests: computations & accuracy

3D GIS models of refraction coefficient



a) 3D model based on location

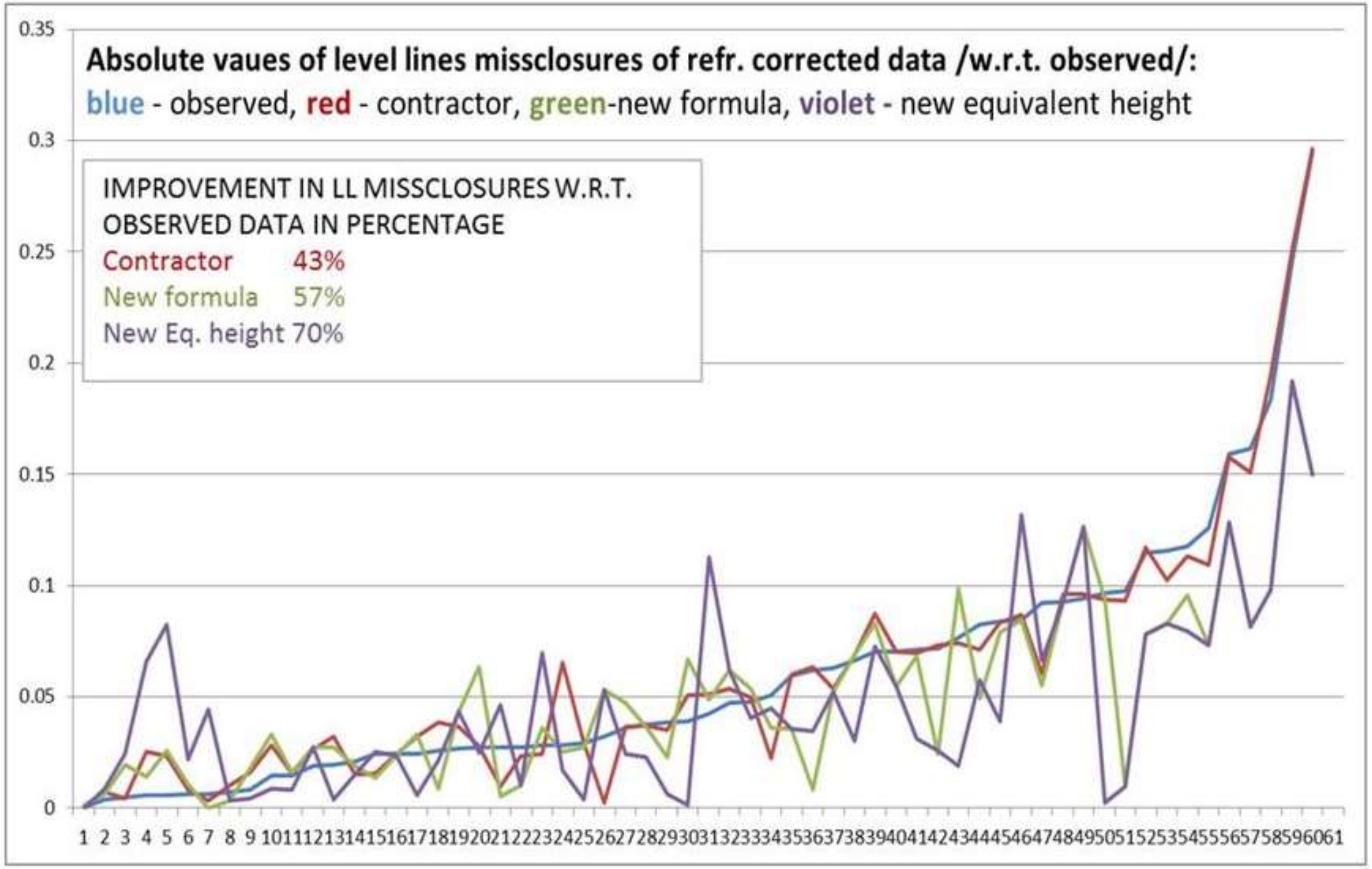


b) 3D model based on location and heights

Field tests: computations & accuracy

Results validation

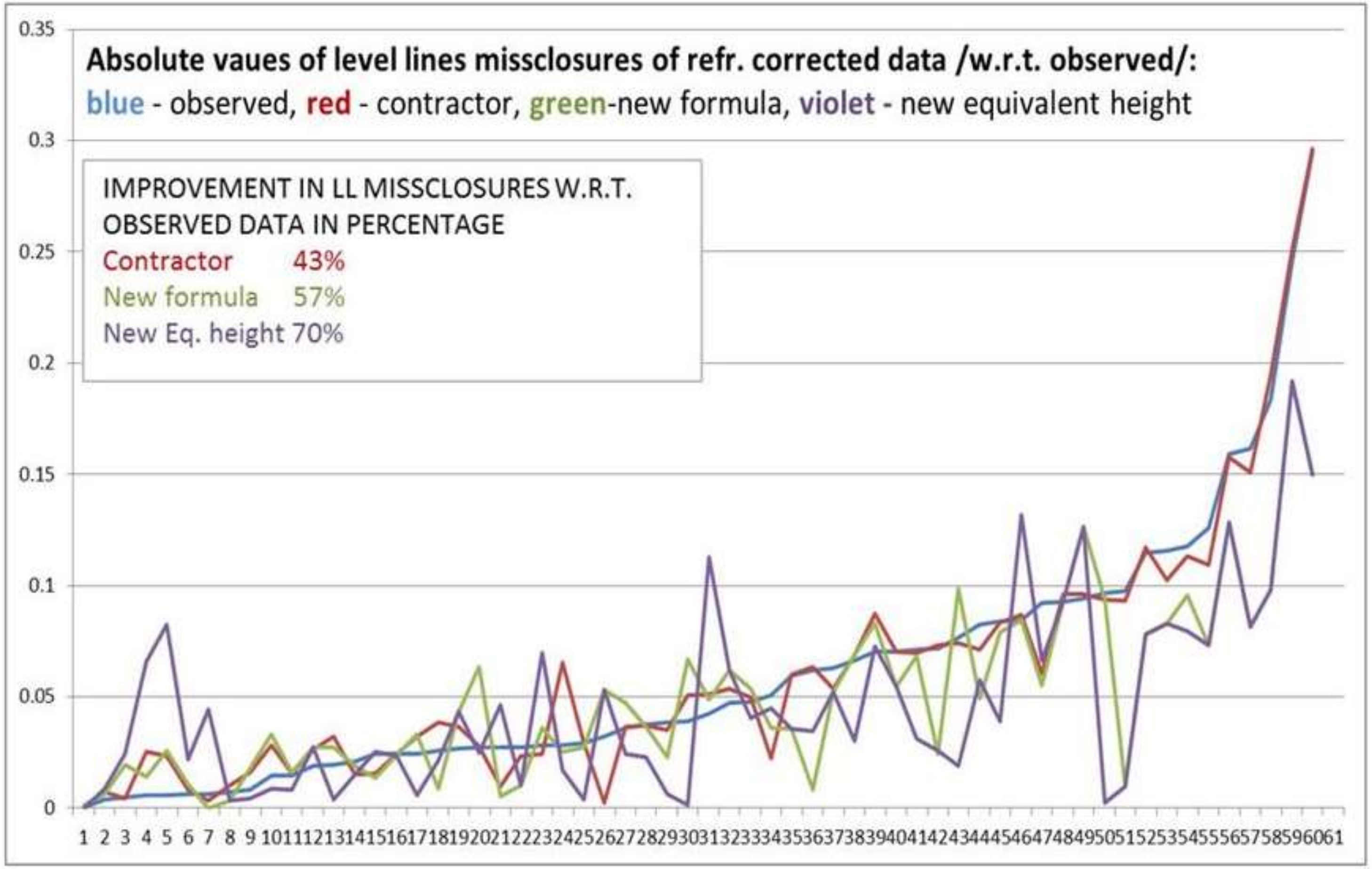
- improvement (60% - 70%) in levelling line misclosures obtained within the height dependent 3D refraction model
- improvement due to equivalent height reaching up to 70% per observed *versus 43% per Contractor's values* of refraction corrections



Field tests: computations & accuracy

Results validation

- loop misclosures decreased with 3-4 cm (70% improvement); the effect of the equivalent height was not considered
- loop misclosures improvement of 30% when the equivalent height was included



Conclusions and recommendations:

- **Four possible scenarios** based on the geodetic application (the desired accuracy of levelling) and the availability of temperature measurements;
- All scenarios need to be tested and validated with respect to their contribution to accuracy improvement on the entire precise levelling network in terms of **adjusted heights.**

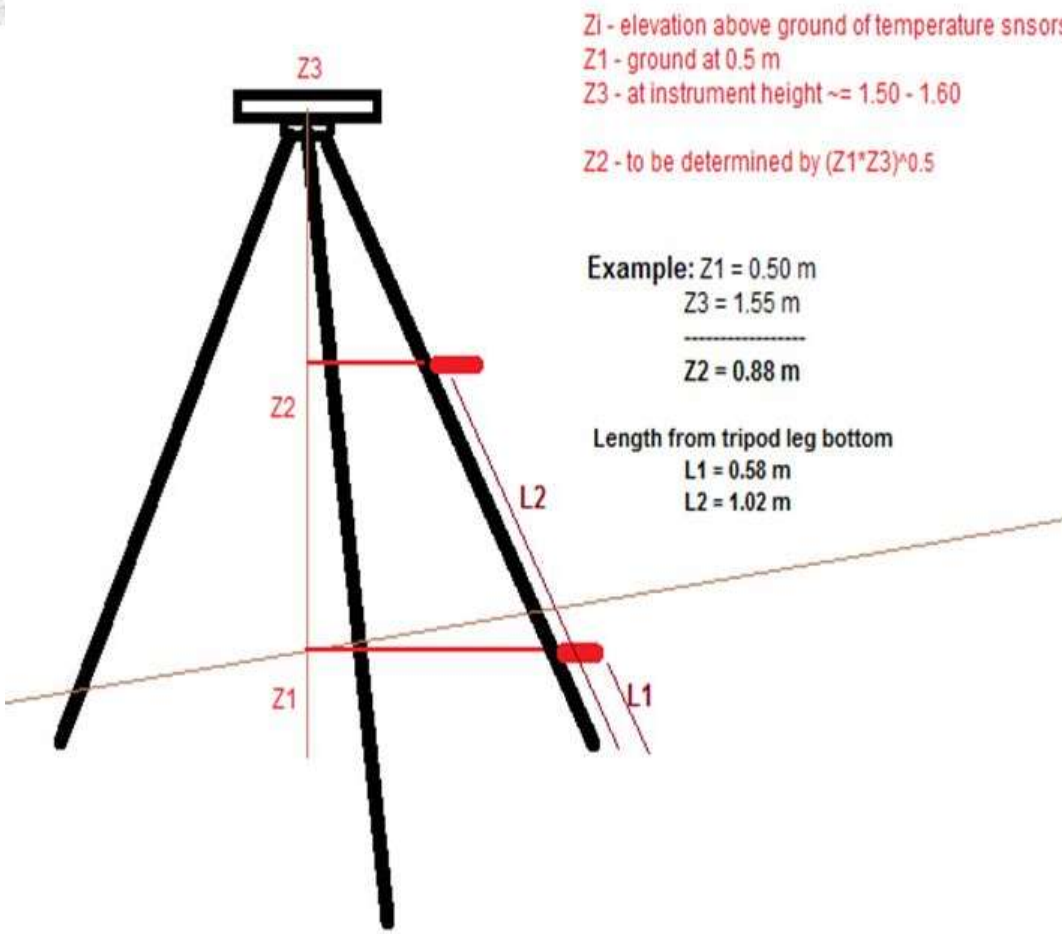
Category of geodetic applications	Height level	Atmosphere	C	Temperature measurements
Low to mid accuracy	All heights	Not considered	-0.41	Not available
General high accuracy: third class precise levelling	Below 800 m	Normal ($t_3 < t_1$)	-0.43	at 2 levels
		Inverse ($t_3 > t_1$)	+0.43	
	Above 800 m	Normal ($t_3 < t_1$)	-0.34	at 2 levels
		Inverse ($t_3 > t_1$)	+0.45	

Conclusions and recommendations:

Category of geodetic applications	**Height level**	**MODEL**	**Temperature measurements**
Utilising refraction coefficient model, depending on temperature readings to determine the type of the atmosphere (sign of ***C***) for first and second order and class precise levelling	Height dependent model	*linear polynomial* *C=func(ΔL;ΔB;H)* *with different coefficients for normal and inverse atmosphere*	at 3 levels
Utilising actual (due to real atmospheric conditions) ***C***-values for first and second order and class precise levelling by: **a) 3D functional model including heights** **b) 2D GIS location dependent model using interpolation facilities**	Location or height dependent models	**a) 3D - FUNCTIONAL MODEL** *linear polynomial* *C=func(ΔL;ΔB;H)* *with coefficients for real atmosphere* **b) 2D GIS LOCATION DEPENDENT MODEL USING INTERPOLATION FACILITIES**	at 2 levels

Conclusions and recommendations:

- For future applications of Kukkamaki's formula, reference levels for the temperature sensors shown in the Figure on the right should are recomended;
- The temperature measurements are needed only to determine the type of the atmosphere (normal or inverse), i.e. the sign of ***C*** *while the actual* ***C*** *come from a RC model;*
- The new formula for computing C could be used as well, providing that the relevant temperature measurements are obtained at reference levels of $z_1 = 0.5$ m, $z_2 = 1.5$ m and $z_3 = 2.5$ m



THANK YOU FOR YOUR ATTENTION!

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