Evaluation of GOCE/GRACE GGMs over Attica and Thessaloniki, Greece, and Wo determination for height system unification

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OUTLINE

Availability of several GOCE/GRACE GGMs for the Earth's potential

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- DIR (R1, R2, R3, R4, R5)
- GOCO (01s, 02s, 03s)
- EIGEN*s/c (51c, 6s/c, 6s/c2, 6c3stat)
- SPW (R1, R2)
- ITG-GOCE02s, GOGRA02s, JYY_GOCE02s

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Validation of the GOCE/GRACE GGMs and Wo determination

- External validation over Greece with collocated GPS/Leveling BMs
- Contribution to $\widehat{W}_o$ LVD determination

E.LE.V.A.T.I.ON Project

Evaluation of the Hel**LE**nic **V**ertical network in the fr**A**me of the European Sys**T**ems and Control Networks **I**nterconnect**ON** – Application in the areas of Attica and Thessaloniki

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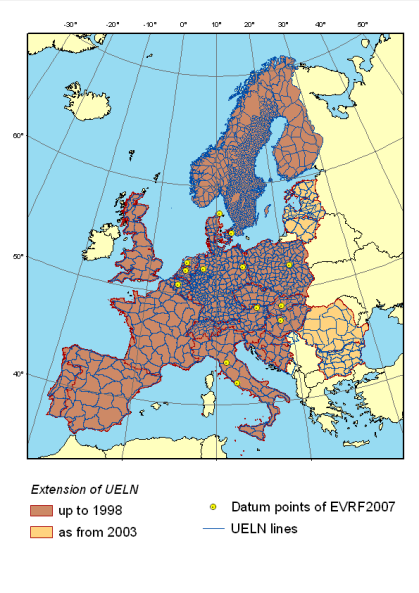
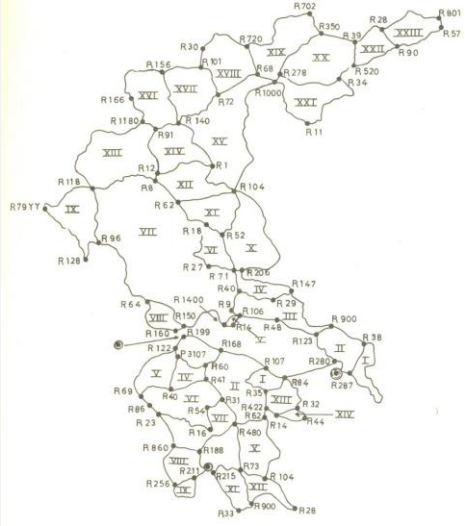


- TEI of Athens – Aristotle University of Thessaloniki – National Technical University of Athens
- The Hellenic VN has not been connected with the EVRS
- Validation before the connection
- GRACE and GOCE data provide valuable information



METHODOLOGY – I

Combined GGM differences to n_{max}=216,000

$$\Delta N = N^{GPS/Lev} - N^{i}\Big|_{2}^{n_1} - N^{EGM2008}\Big|_{n_1+1}^{2160} - N^{RTM} - N_o$$

$N^{i}\Big|_{2}^{n_1}$ evaluation of GOCE/GRACE GGMs every 1 degree

N^{RTM} from a 3″ DTM over Greece

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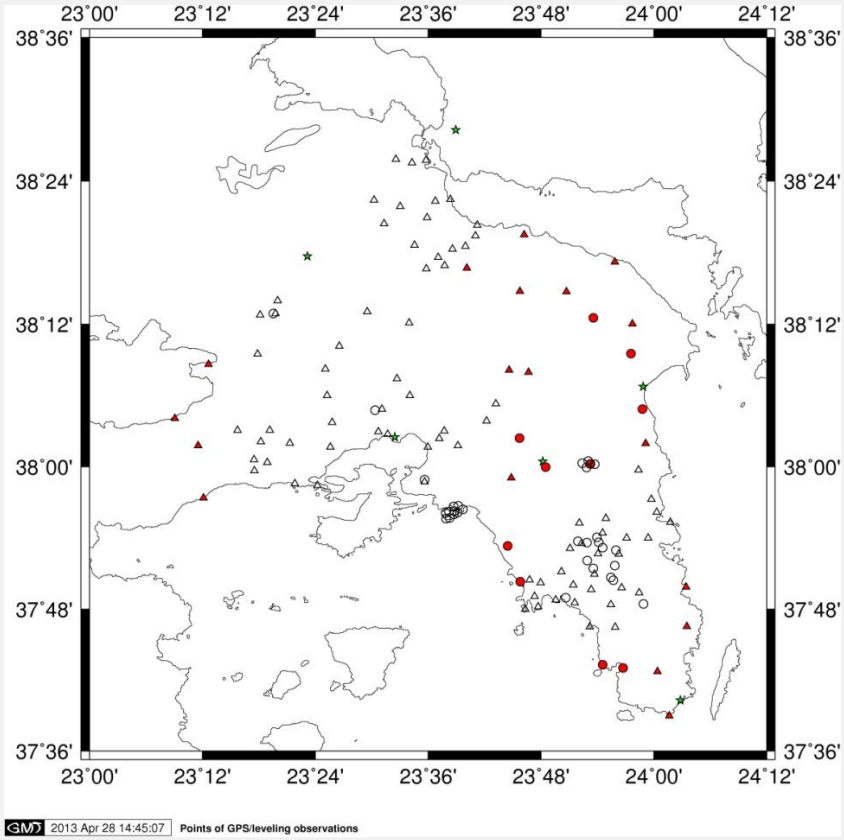
$N^{i}\Big|_{2}^{n_1}$ evaluation of GOCE/GRACE GGMs every 1 degree

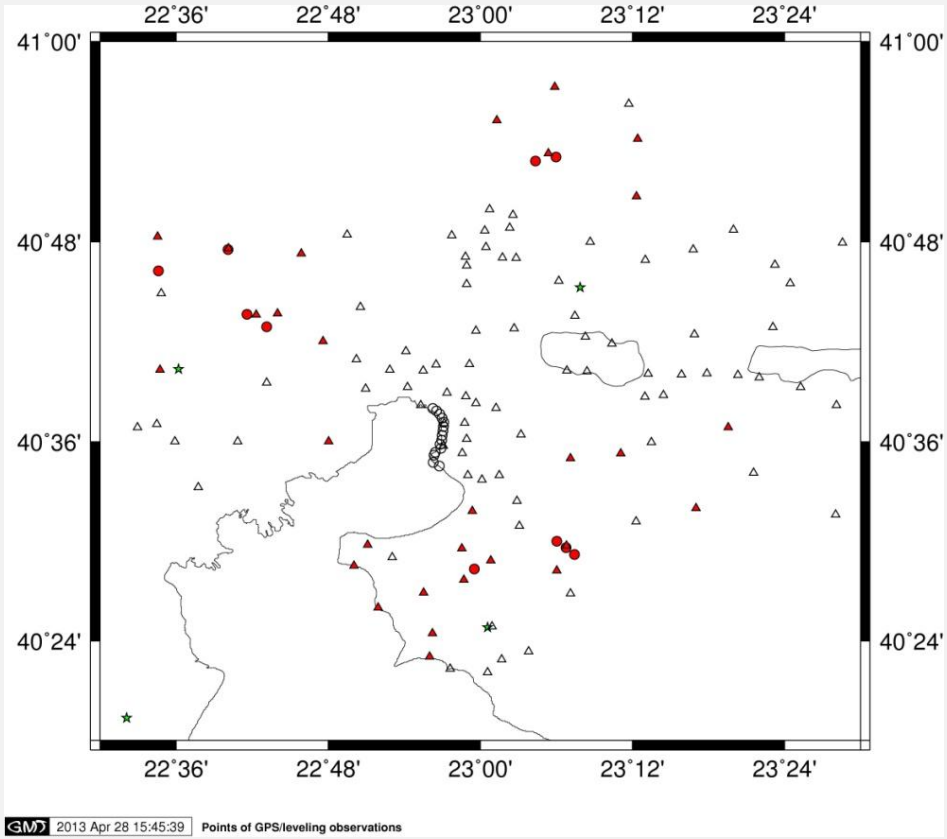
N^{RTM} from a 3″ DTM over Greece

- Mean Tide to Tide Free conversion for orthometric heights
- GGM Zero Tide to Tide Free when necessary
- All computations in GRS80
- N_o relative to the IERS W_o of 62636856.0 m^2/s^2

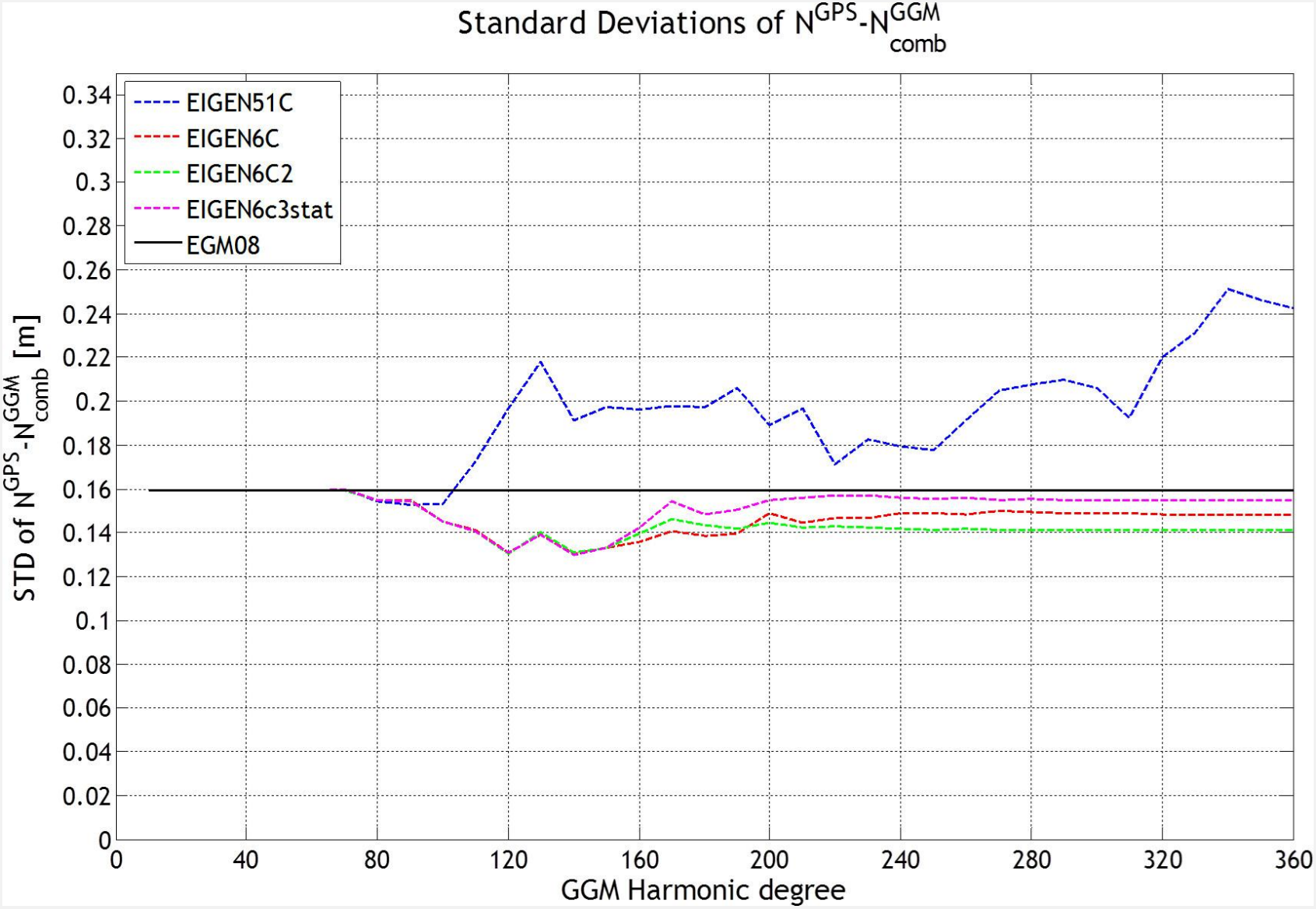
GPS/LEVELING BMs

2 tests areas 100 km × 100 km each – 230 BMs





GOCE/GRACE GGM VALIDATION



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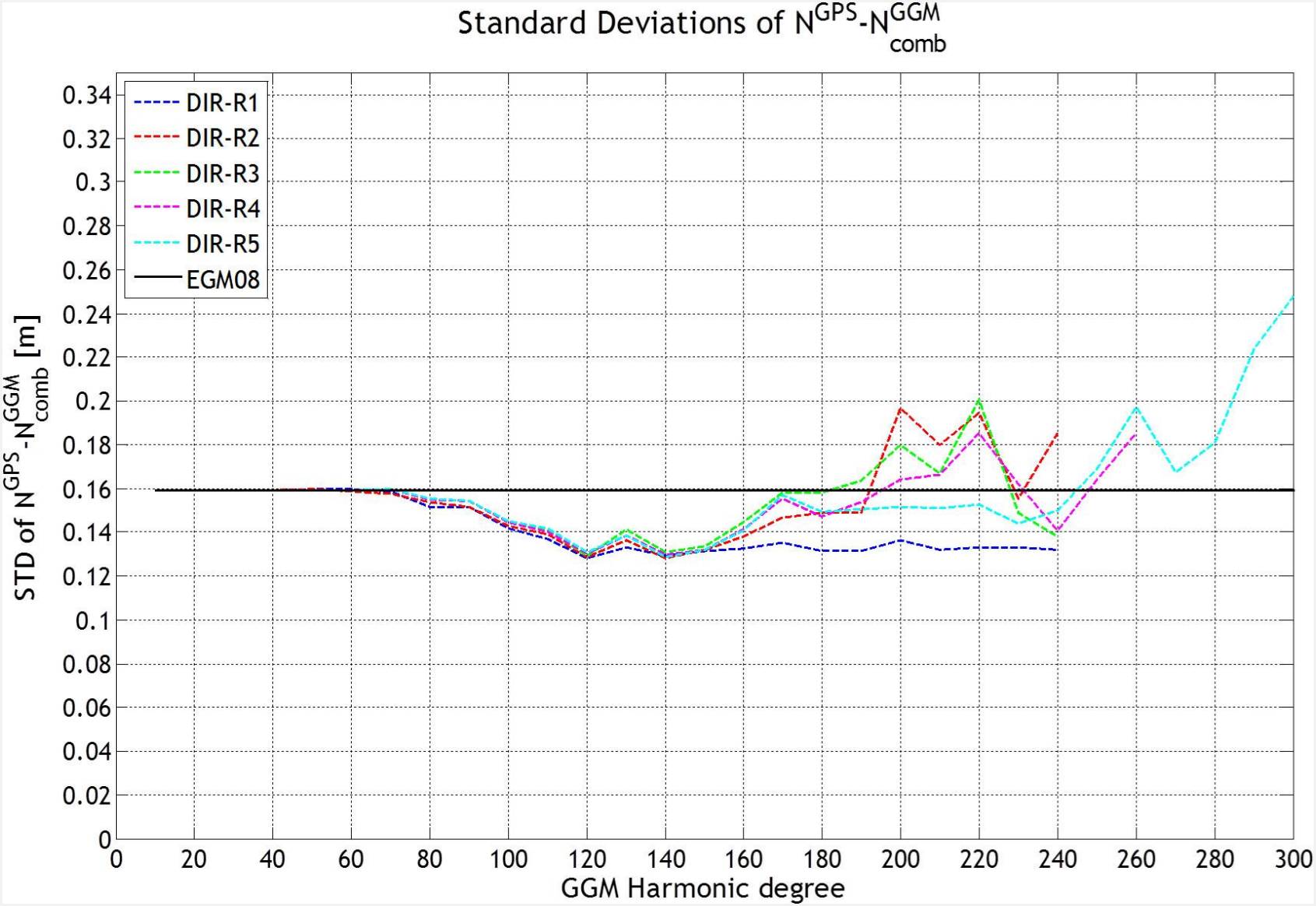

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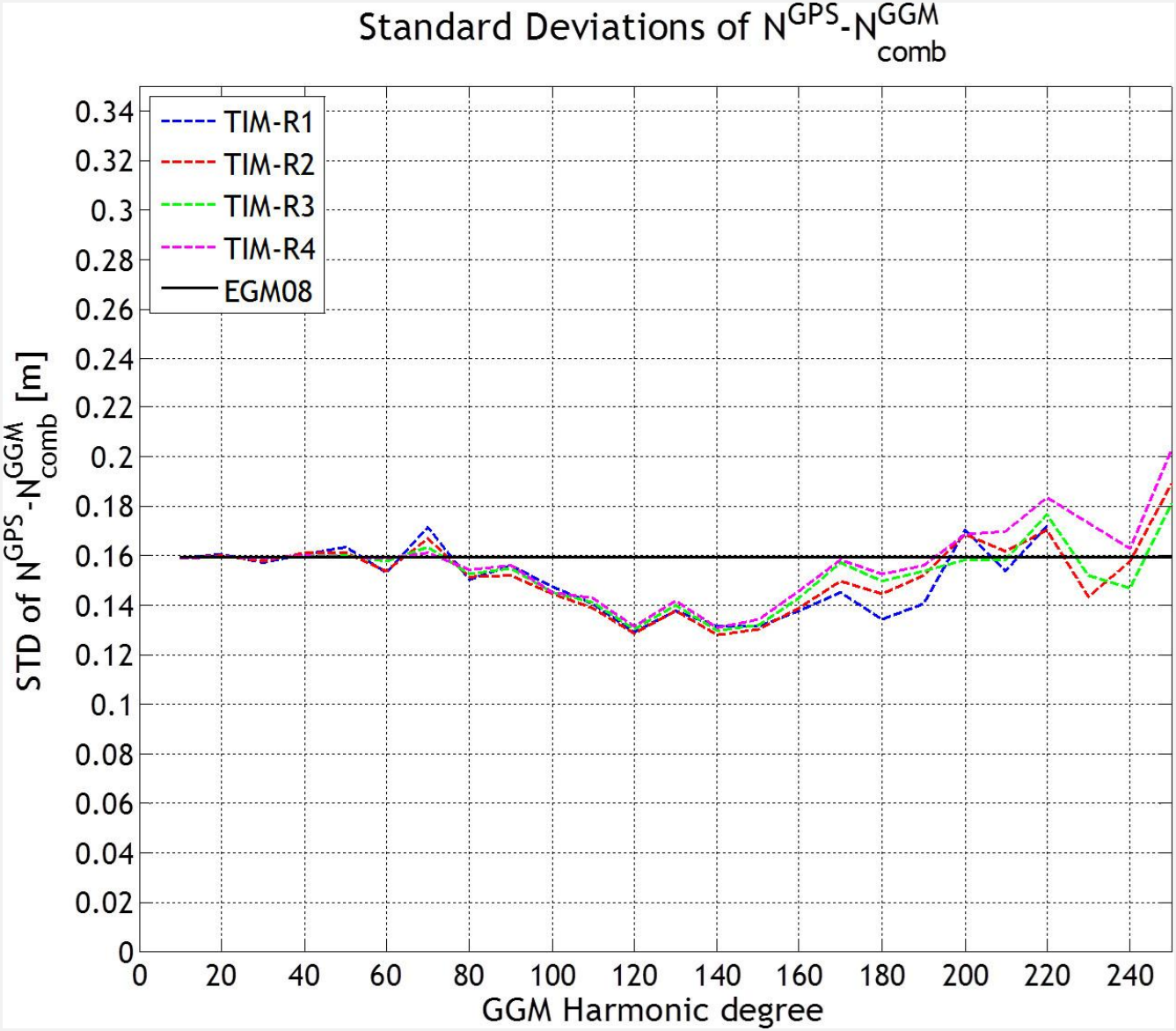

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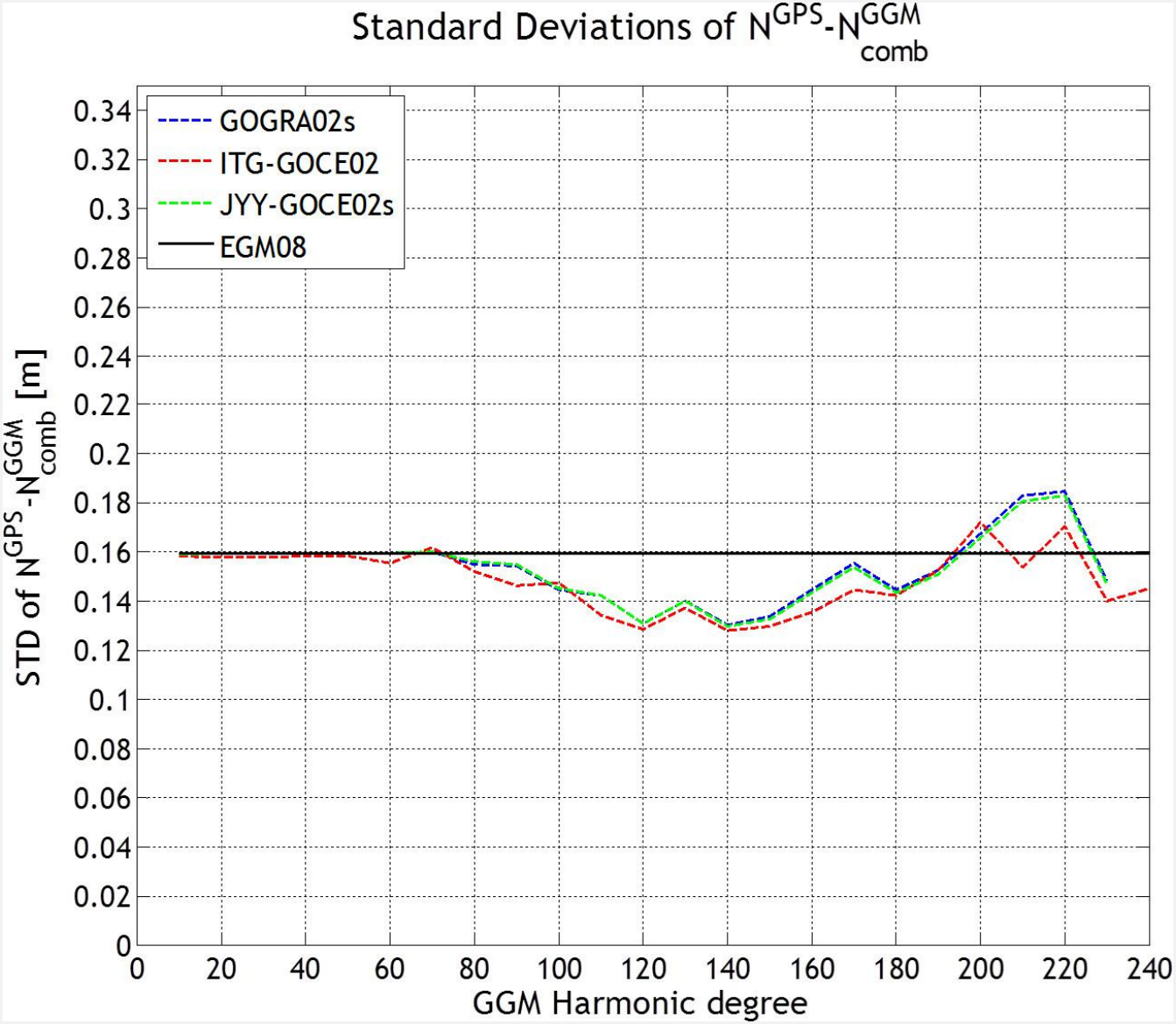

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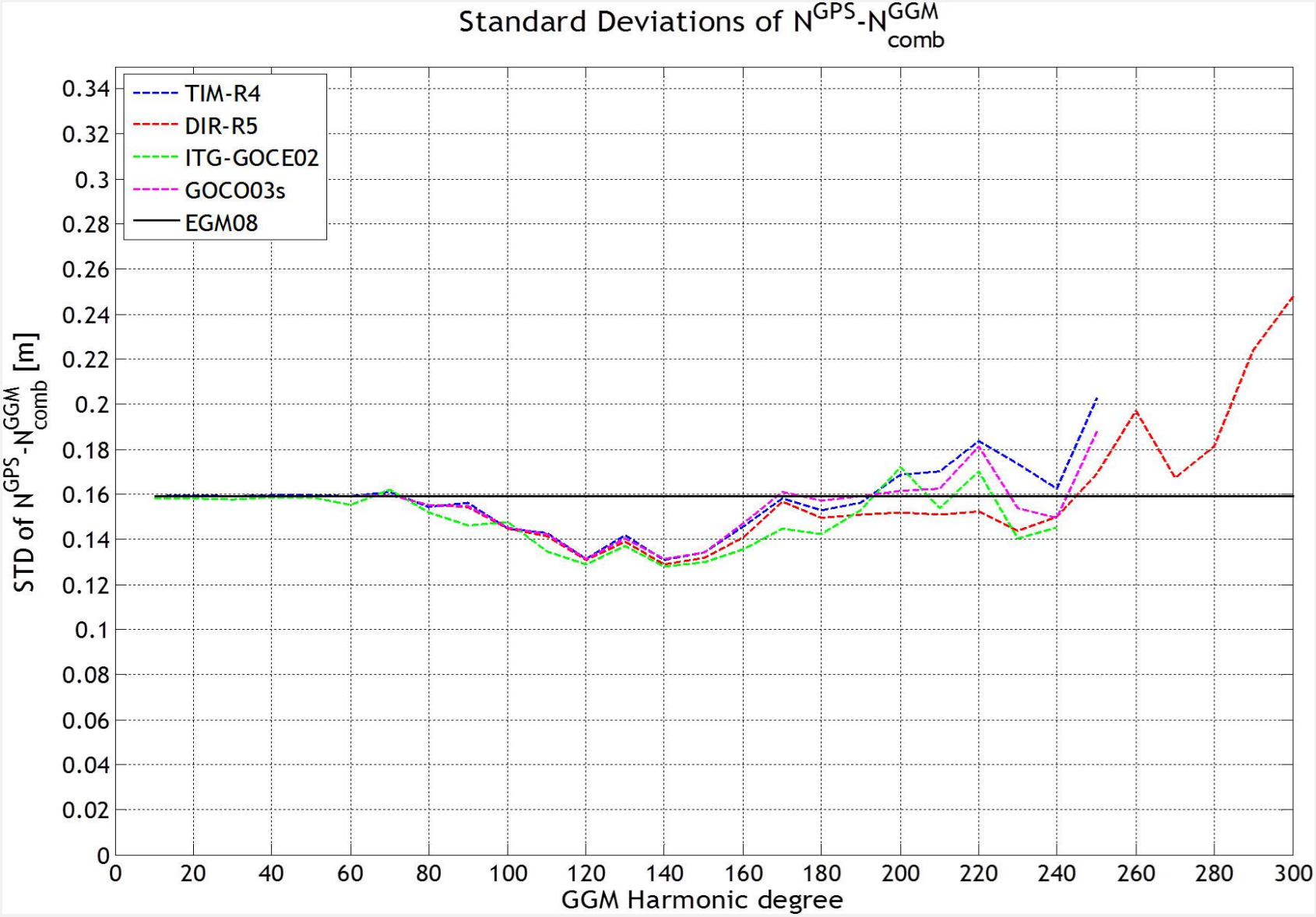


GOCE/GRACE GGM VALIDATION

Geoid height differences between GOCE/GRACE GGMs and GPS/Lev BMs. Unit [m]

GGM	d/o	range	mean	std
EGM2008	2190	1.107	-0.505	±0.159
DIR-R5	140+EGM08	0.736	-0.469	±0.128
TIM-R4	140+EGM08	0.729	-0.505	±0.131
GOCO03s	140+EGM08	0.734	-0.473	±0.131
ITG-GOCE02s	140+EGM08	0.728	-0.469	±0.127
EIGEN6c3	140+EGM08	0.731	-0.464	±0.129

METHODOLOGY – II

Basic physical model (Helmert ortho heights):

$$H_i^{helm} = \frac{W_o^{LVD} - W_i}{g_i + 0.0424 \cdot 10^{-5} H_i^{helm}} = \frac{W_o^{LVD} - W_i}{\bar{g}_i}$$

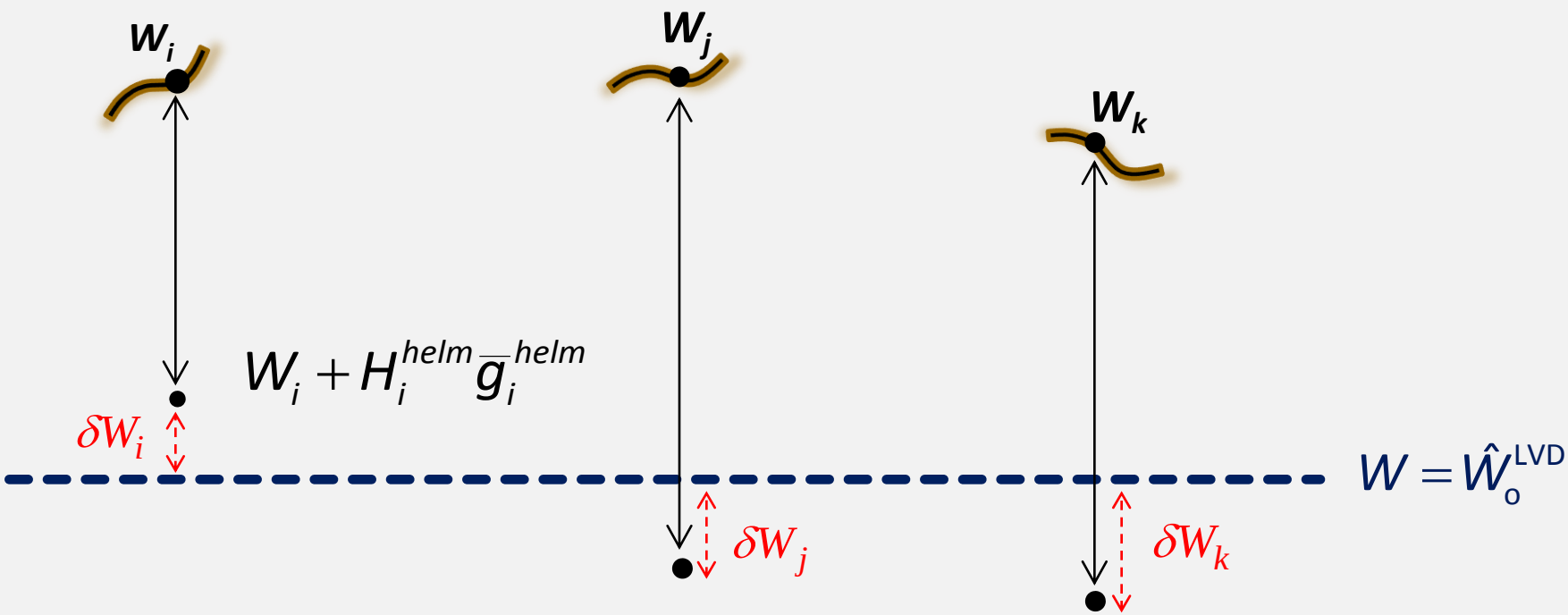
LS estimate of LVD's zero-height level

$$\hat{W}_o^{LVD} = \frac{\sum_i p_i y_i}{\sum_i p_i}$$

$y_i \longrightarrow W_i + H_i^{helm} \bar{g}_i^{helm}$

$p_i \longrightarrow$ **'weights'**

Method's rationale



Estimate the LVD zero-height level such that: $\sum_i p_i \, \delta W_i^2 = \min$

HELLENIC LVD

The Hellenic (*local*) VD was established by HMGS within the period 1963-1986

In principle, physical heights in the HVD were modeled as Helmert orthometric heights

An unknown W_o value is associated with the HVD

The Helmert orthometric heights refer to the TG station at the Piraeus port (Athens) – MSL measurements were performed over the period 1933-1978

The true accuracy of the HVD's leveling network is largely unknown

Numerical Results I

Un-weighted LS estimate

- *EGM2008 (2190)* $\hat{W}_O^{LVD} = 62636860.77 \pm 0.4 \mathrm{m}^2/s^2$
- EGM2008 (260) $\hat{W}_O^{LVD} = 62636859.43 \pm 0.4 \mathrm{m}^2/s^2$
- DIR-R4 (260) $\hat{W}_O^{LVD} = 62636859.90 \pm 0.4 \mathrm{m}^2/s^2$
- TIM-R4 (250) $\hat{W}_O^{LVD} = 62636860.50 \pm 0.4 \mathrm{m}^2/s^2$
- DIR-R5 (300) $\hat{W}_O^{LVD} = 62636860.01 \pm 0.4 \mathrm{m}^2/s^2$

Numerical Results I

Height residuals relative to $\hat{W}_o^{LVD}$ from EGM2008 (2190) [Units: m]

$$e_i = H_i^{helm} - \frac{\hat{W}_o^{LVD} - W_i}{\bar{g}_i^{helm}}$$

GGM	max	min	mean	std
EGM2008 (2190)	0.481	-0.386	0.000	±0.172
EGM2008 (260)	1.398	-1.041	-0.137	±0.411
TIM-R4	1.385	-0.833	-0.027	±0.414
DIR-R4	1.240	-1.019	-0.089	±0.363
DIR-R5	1.352	-1.044	-0.078	±0.395

Numerical Results II

Un-weighted LS estimate & combined GOCE/GRACE GGMs

- *EGM2008 (2190)* $\hat{W}_O^{LVD} = 62636860.77 \pm 0.4 \mathrm{m}^2/s^2$
- EGM2008 (260) $\hat{W}_O^{LVD} = 62636859.43 \pm 0.4 \mathrm{m}^2/s^2$
- DIR-R4 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.39 \pm 0.4 \mathrm{m}^2/s^2$
- TIM-R4 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.43 \pm 0.4 \mathrm{m}^2/s^2$
- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.42 \pm 0.4 \mathrm{m}^2/s^2$

Numerical Results II

Un-weighted LS estimate & combined GOCE/GRACE GGMs

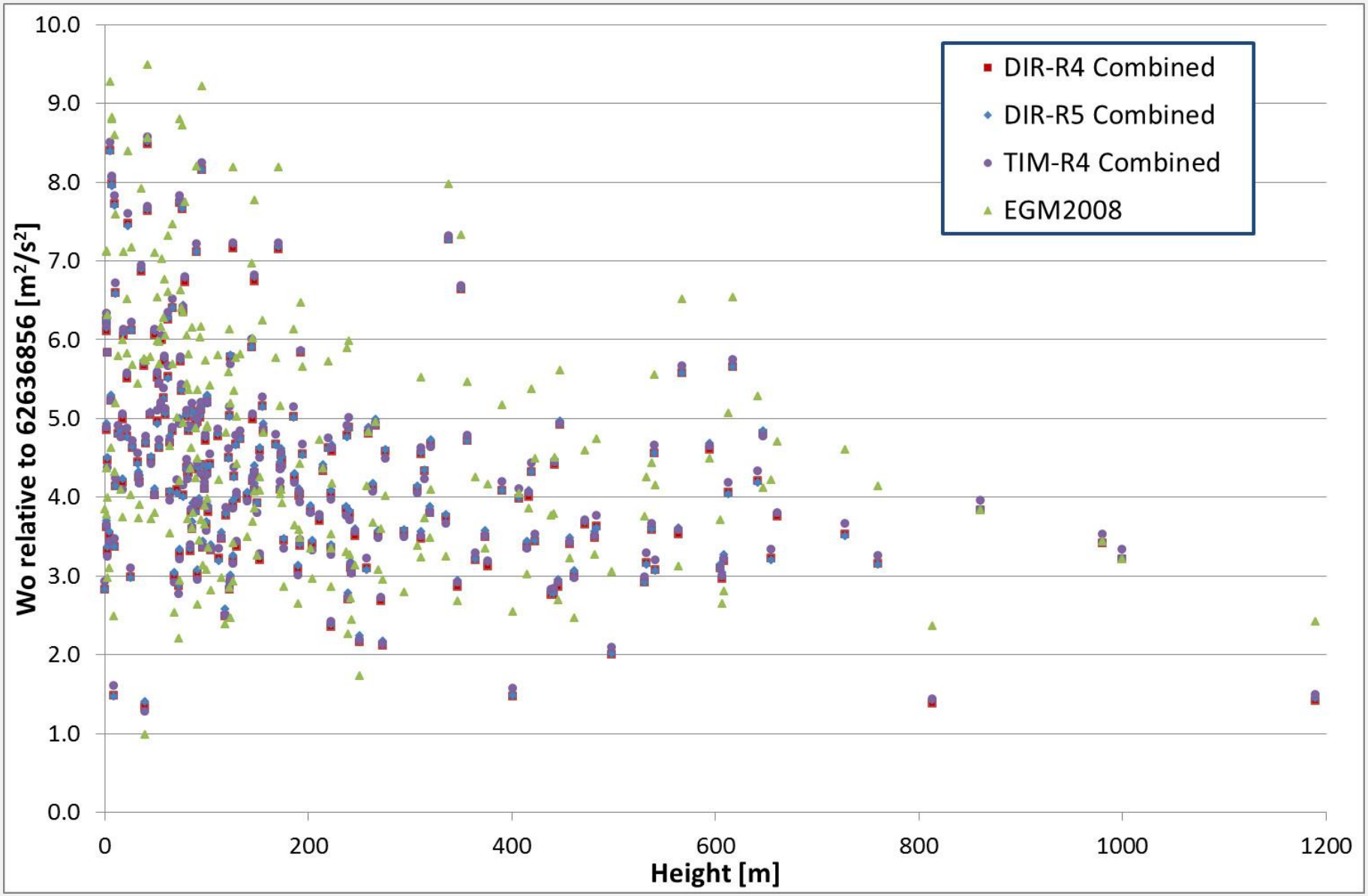
- *EGM2008 (2190)* $\hat{W}_O^{LVD} = 62636860.77 \pm 0.4 \mathrm{m}^2/s^2$

- DIR-R4 (140)+EGM08 $\delta\hat{W}_O^{LVD} \approx 3.8cm$

- TIM-R4 (140)+EGM08 $\delta\hat{W}_O^{LVD} \approx 3.4cm$

- DIR-R5 (140)+EGM08 $\delta\hat{W}_O^{LVD} \approx 3.5cm$

Numerical Results II



Un-weighted LS estimate with a height dependent parameter & combined GOCE/GRACE GGMs

$$H_i^{helm} = \frac{W_o^{LVD} - W_i}{g_i + 0.0424 \cdot 10^{-5} H_i^{helm}} = \frac{W_o^{LVD} - W_i}{\bar{g}_i^{helm}} + \lambda H_i^{helm}$$

Un-weighted LS estimate with a height dependent parameter & combined GOCE/GRACE GGMs

- *EGM2008 (2190)* $\hat{W}_O^{LVD} = 62636860.77 \pm 0.4 \mathrm{m}^2/s^2$

- DIR-R4 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.92 \pm 0.008 \mathrm{m}^2/s^2$

  $\lambda = (2.559 \pm 0.009) \times 10^{-4} \mathrm{m}^2/s^2$

- TIM-R4 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.96 \pm 0.008 \mathrm{m}^2/s^2$

  $\lambda = (2.558 \pm 0.009) \times 10^{-4} \mathrm{m}^2/s^2$

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.95 \pm 0.008 \mathrm{m}^2/s^2$

  $\lambda = (2.552 \pm 0.009) \times 10^{-4} \mathrm{m}^2/s^2$

Numerical Results III

Un-weighted LS estimate with a height dependent parameter & combined GOCE/GRACE GGMs

- DIR-R4 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.92 \pm 0.008 \mathrm{m}^2/s^2$
- TIM-R4 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.96 \pm 0.008 \mathrm{m}^2/s^2$
- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.95 \pm 0.008 \mathrm{m}^2/s^2$

Great consistency for the GOCE/GRACE GGMs in $\hat{W}_O^{LVD}$

$$\delta\hat{W}_O^{LVD} \approx 0.3 - 0.4\,cm$$

Numerical Results III

Un-weighted LS estimate with a height dependent parameter & combined GOCE/GRACE GGMs

$$e_i = H_i^{helm} - \frac{\hat{W}_o^{LVD} - W_i}{\bar{g}_i^{helm}} - \hat{\lambda} H_i^{helm}$$

Height residuals relative to $\hat{W}_o^{LVD}$ from EGM2008 (2190) [Units: m]

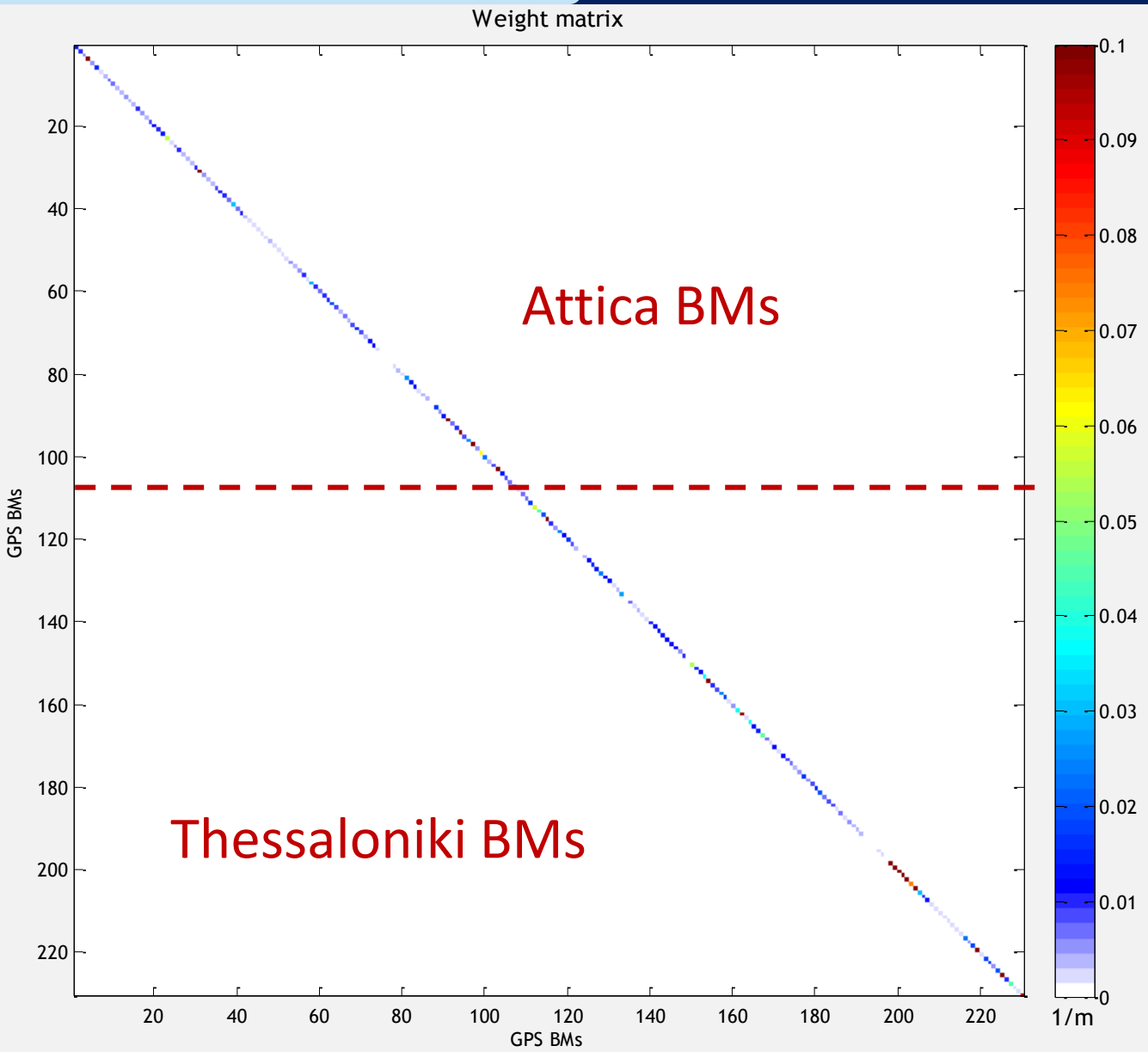
GGM	max	min	mean	std
EGM2008 (2190)	0.481	-0.386	0.000	±0.172
TIM-R4	0.398	-0.346	-0.019	±0.128
DIR-R4	0.390	-0.340	-0.016	±0.126
DIR-R5	0.393	-0.334	-0.019	±0.125

Weighted LS estimate with $\mathbf{p}_i = 1/\mathbf{H}_i^{helm}$, a height dependent parameter & combined GOCE/GRACE GGMs

Weighted LS estimate with $\mathbf{p}_i = 1/\mathbf{H}_i^{helm}$, a height dependent parameter & combined GOCE/GRACE GGMs

- DIR-R5 combined with EGM2008 provides the overall best results w.r.t. the differences with the GPS/Lev BMs.
- It will be the one used to carry-out the weighted LS adjustment

Numerical Results IV



Weighted LS estimate with $\mathbf{p}_i = 1/\mathbf{H}_i^{helm}$, a height dependent parameter & combined GOCE/GRACE GGMs

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.95 \pm 0.008 \mathrm{m}^2/s^2$

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.94 \pm 0.002 \mathrm{m}^2/s^2$

  $p_i = 1/H_i^{helm}$

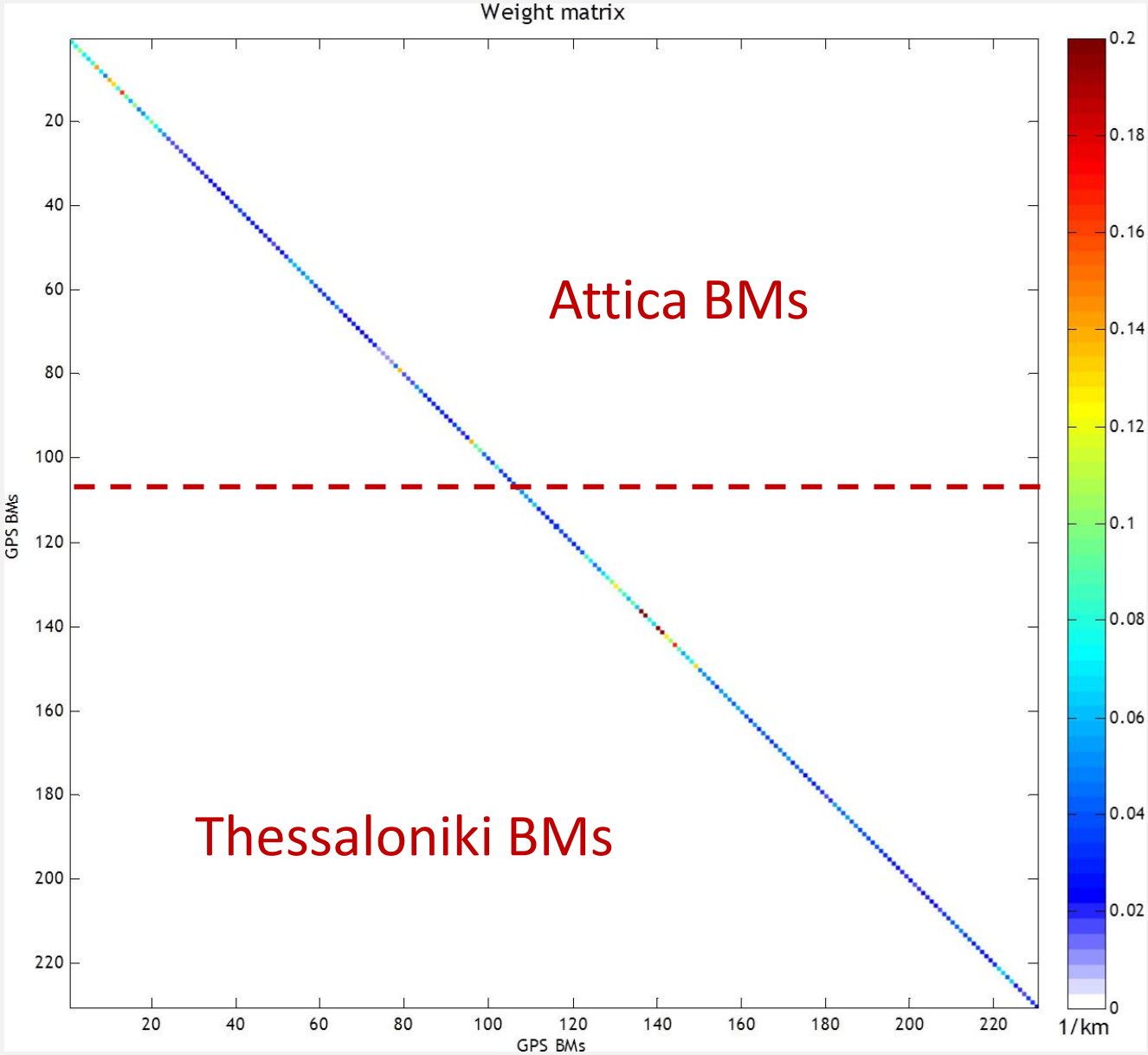
$$\delta\hat{W}_O^{LVD} \approx 0.1cm$$

Weighted LS estimate with $p_i = 1/L_i$, a height dependent parameter & combined GOCE/GRACE GGMs

- L_i [km] denotes the distances from the Piraeus and Thessaloniki TGs

GGM	max	min	mean	std
Attica	103.774	6.097	33.729	±20.416
Thessaloniki	56.553	2.814	26.540	±12.428

Numerical Results IV



Numerical Results IV

Weighted LS estimate with $\mathbf{p}_i = 1/\mathbf{H}_i^{helm}$, $\mathbf{p}_i = 1/\mathbf{L}_i$ a height dependent parameter & combined GOCE/GRACE GGMs

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.95 \pm 0.008 \mathrm{m}^2/s^2$

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.94 \pm 0.002 \mathrm{m}^2/s^2$

  $p_i = 1/H_i^{helm}$

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.92 \pm 0.002 \mathrm{m}^2/s^2$

  $p_i = 1/L_i$

$$\delta\hat{W}_O^{LVD} \approx 0.1 - 0.3 cm$$

Numerical Results IV

Our final $\hat{W}_o^{LVD}$ estimate for Greece is

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.95 \pm 0.008 \mathrm{m}^2/s^2$

Numerical Results IV

Our final $\hat{W}_o^{LVD}$ estimate for Greece is

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD} = 62636860.95 \pm 0.008 \mathrm{m}^2/s^2$

Estimating $\hat{W}_o^{LVD}$ separately for Attica and Thessaloniki

- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD}(Attica) = 62636860.31 \pm 0.021 \mathrm{m}^2/s^2$
- DIR-R5 (140)+EGM08 $\hat{W}_O^{LVD}(Thess.) = 62636860.79 \pm 0.017 \mathrm{m}^2/s^2$

$$\delta\hat{W}_O^{LVD} \approx 4.8 cm \qquad \delta MSL \approx 2.5 cm$$

CONCLUSIONS

- Latest GOCE/GRACE GGM validation over Greece and Wo determination using various data/weight combinations

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- DIR-R5 is better up to d/o 245 with significant improvement in the spectral range between d/o 185-230

CONCLUSIONS

- Latest GOCE/GRACE GGM validation over Greece and Wo determination using various data/weight combinations

- The latest releases of the GOCE/GRACE GGMs are better as much as 3 cm compared to EGM2008

- DIR-R5 is better up to d/o 245 with significant improvement in the spectral range between d/o 185-230

- $\hat{\mathbf{W}}_o^{LVD}$ from GOCE GGMs is more robust compared to EGM2008, with $\delta\hat{W}_O^{LVD}$ between the various GGMs at 0.3-0.4 cm and for DIR-R5, between the various weight schemes, at 0.1 cm

Thank you for your attention

ACKNOWLEDGEMENT

E.LE.V.A.T.I.ON. Project

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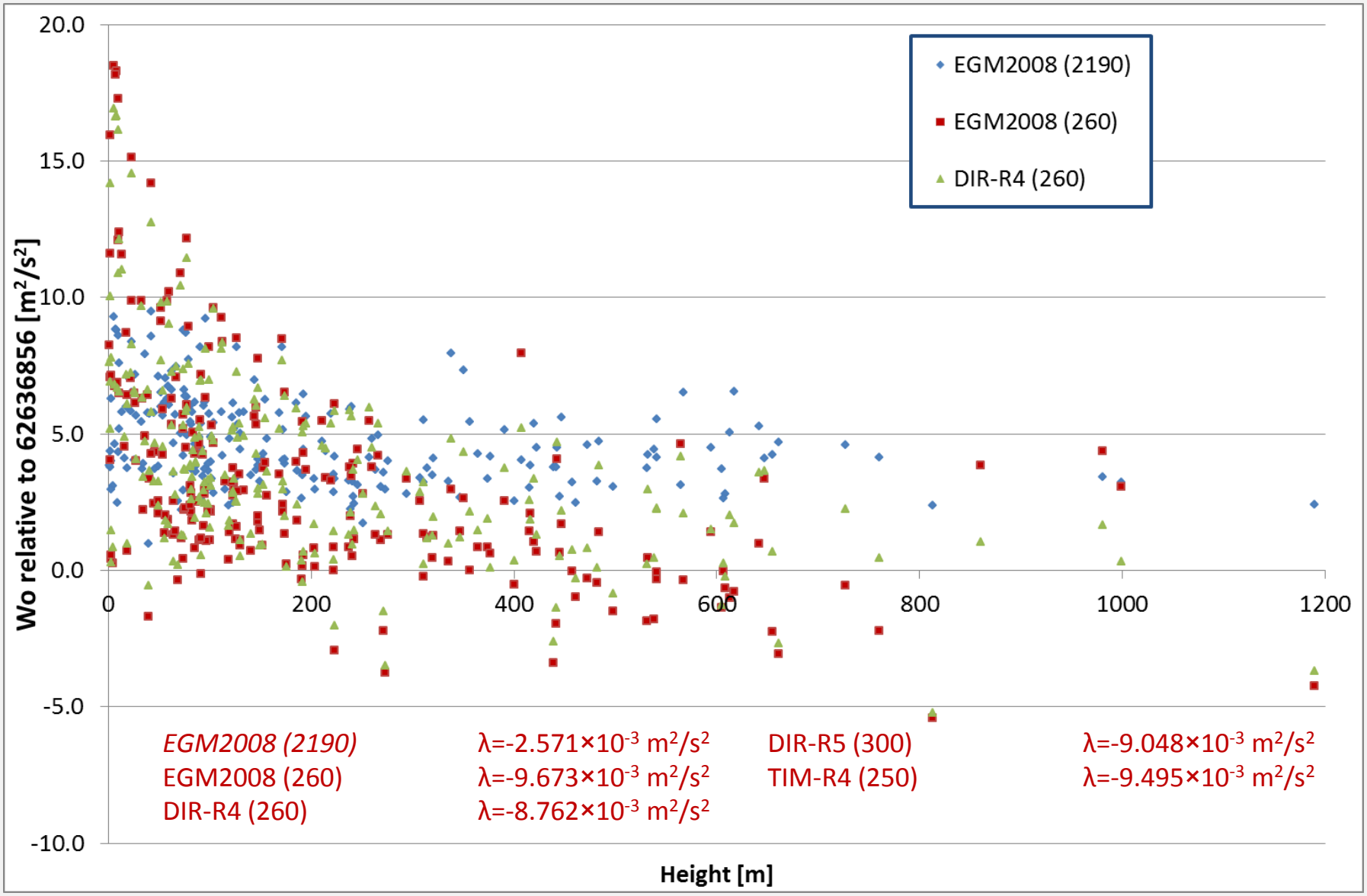
BACK-UP SLIDES

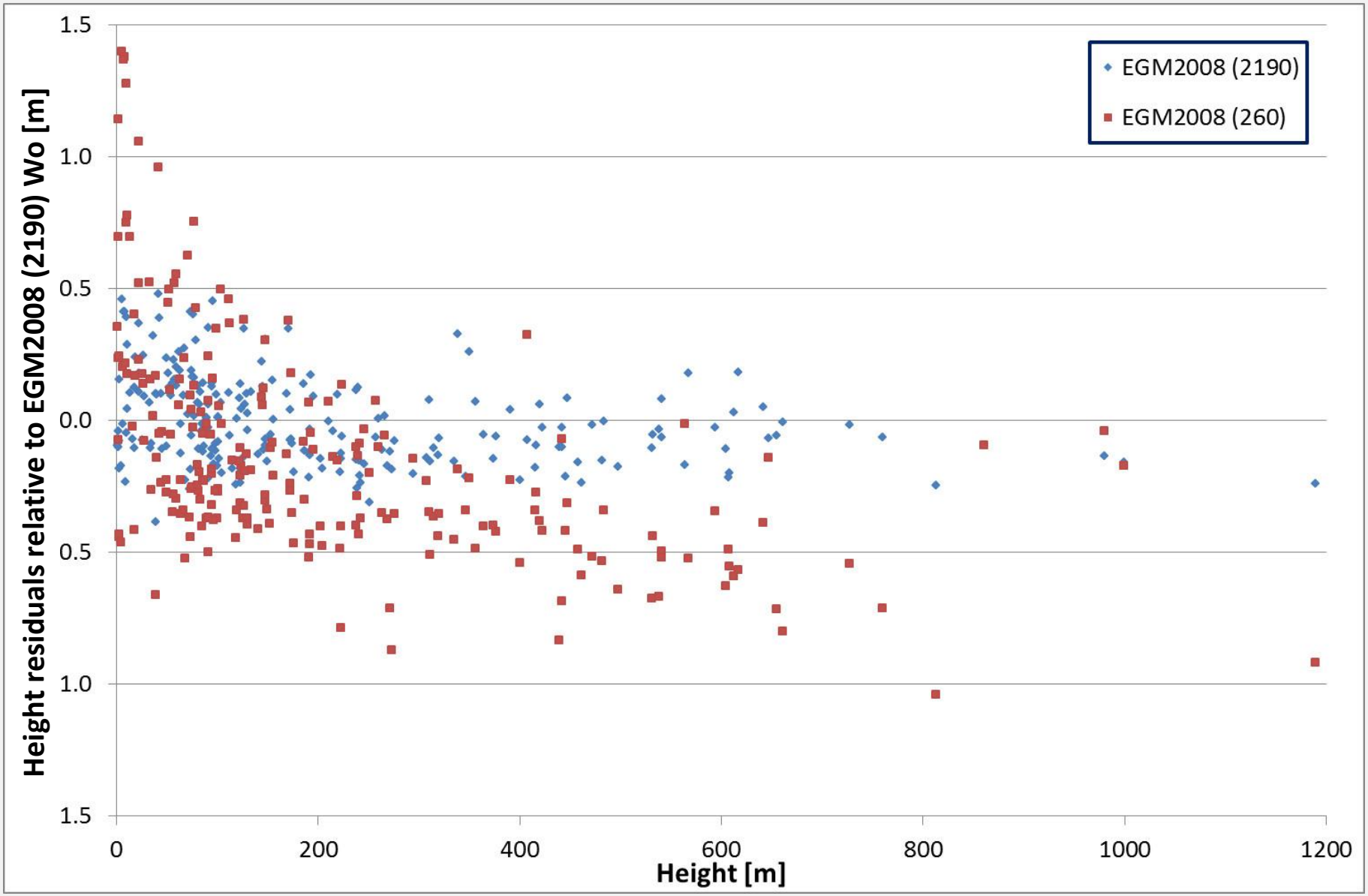
Numerical Results I



Numerical Results I

Wo residuals relative to $\hat{W}_o^{LVD}$ from EGM2008 (2190)

Numerical Results I



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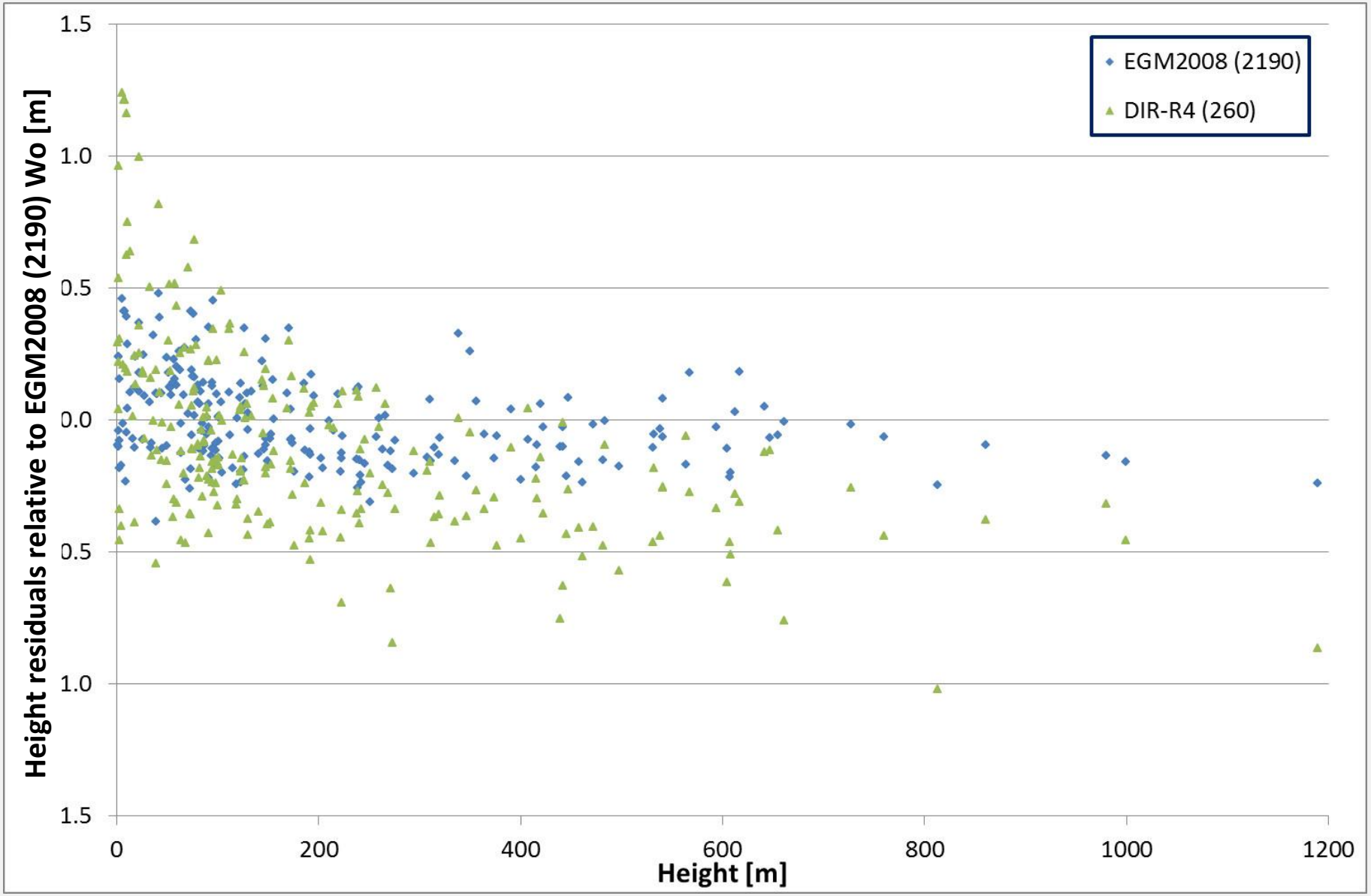

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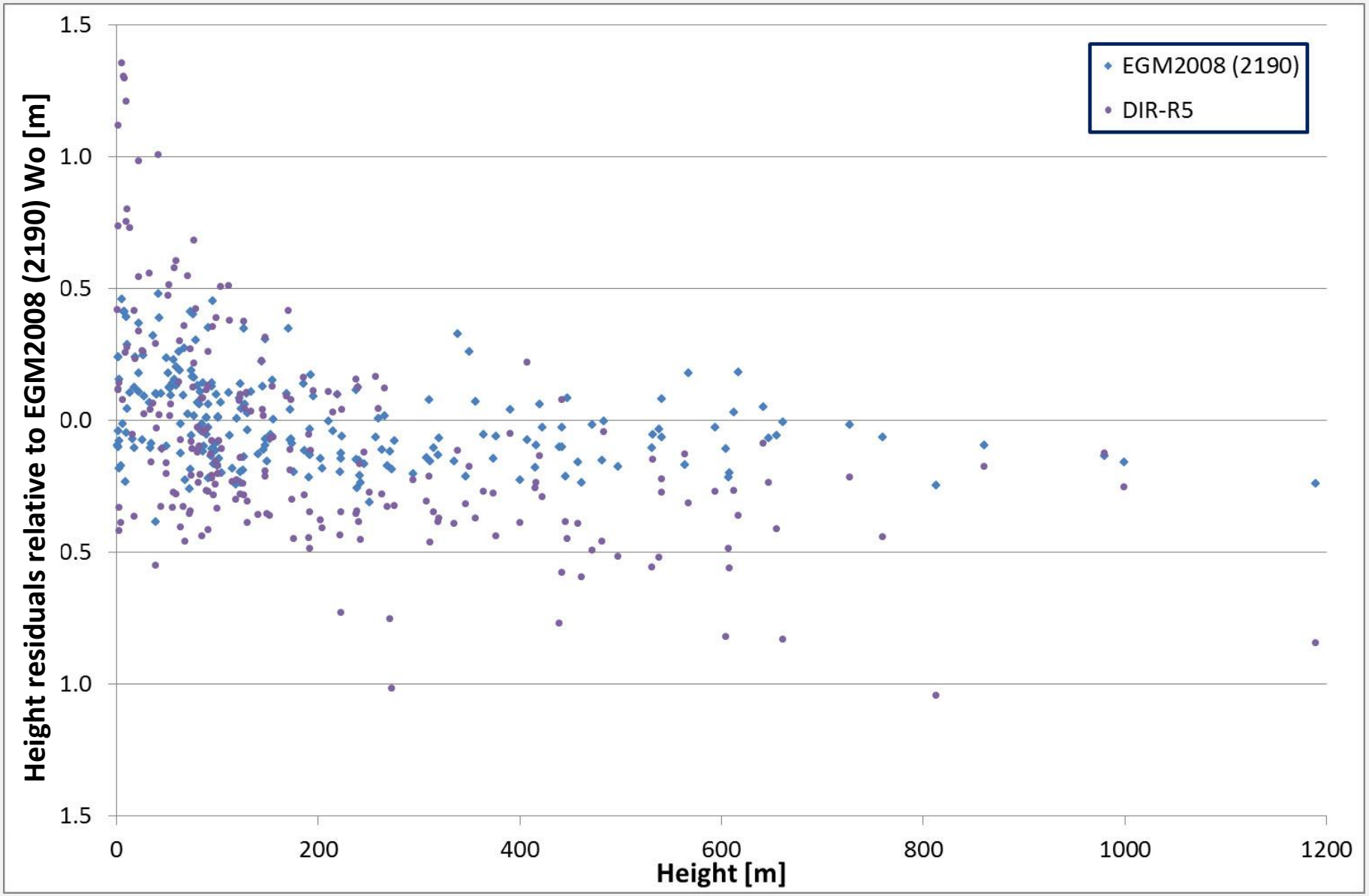

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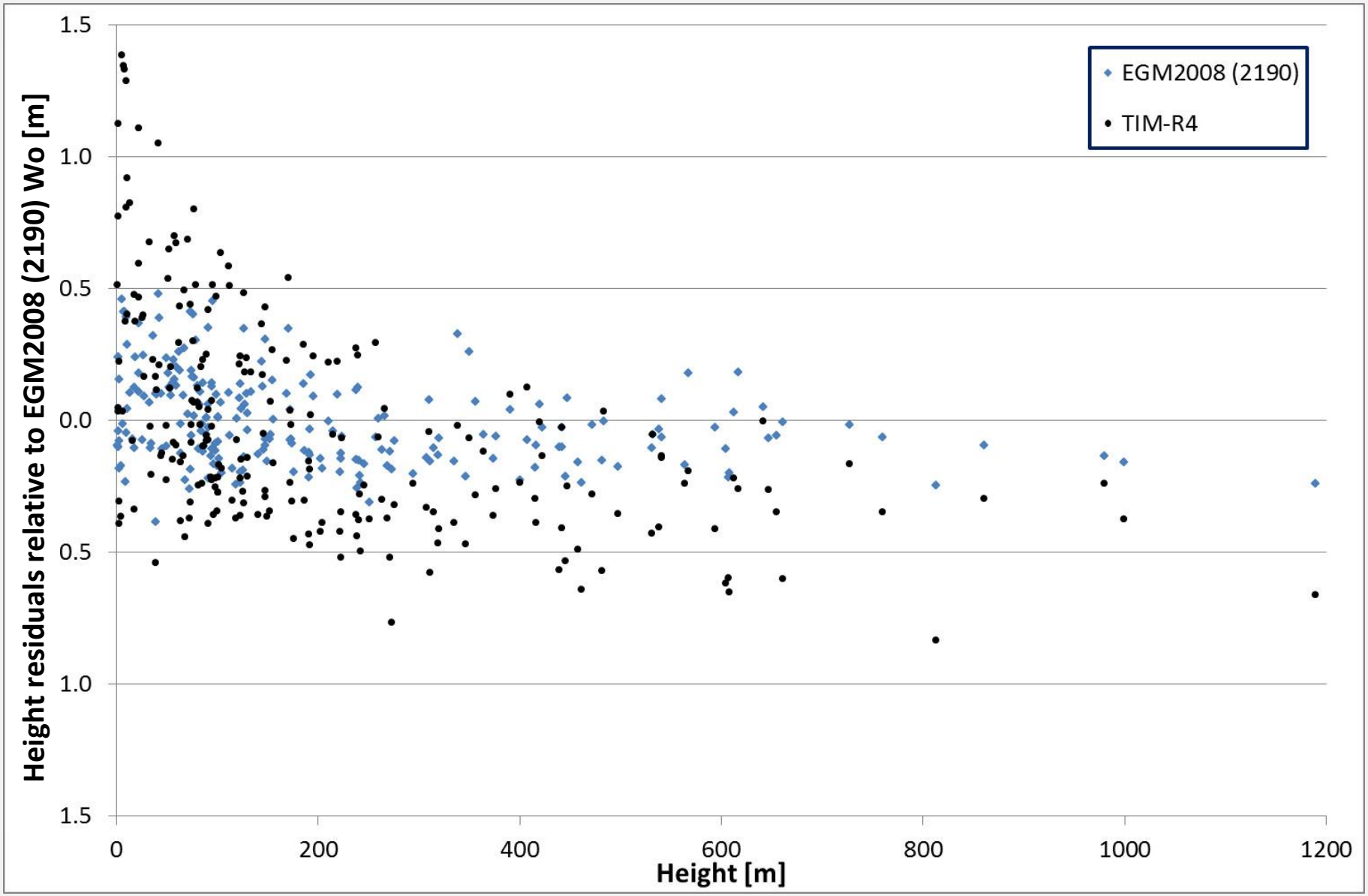
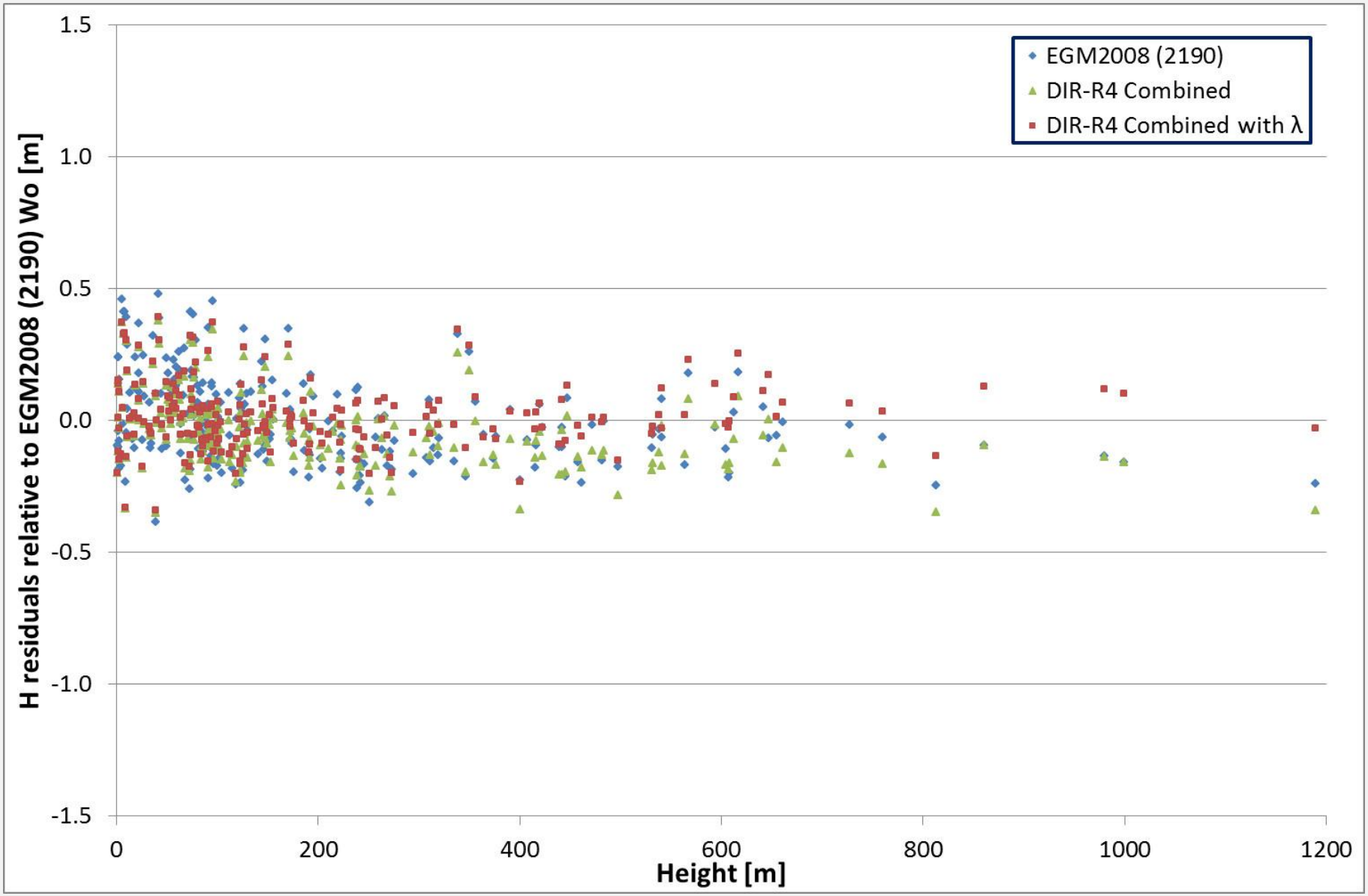


Numerical Results III



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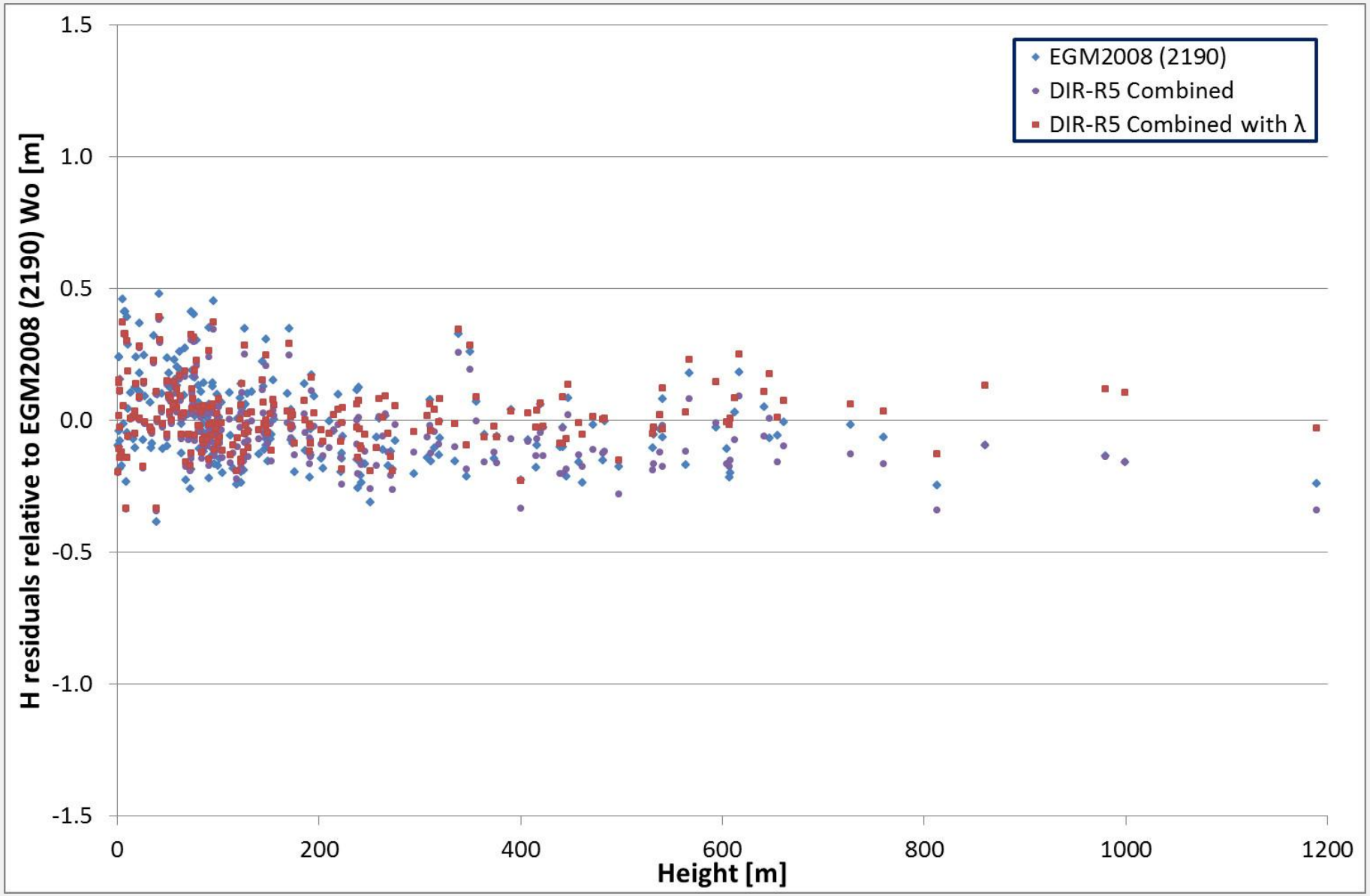

Numerical Results III