


Wrocław University of Environmental and Life Sciences

DETERMINING THE HEIGHTS AND HORIZONTAL POSITIONS OF TATRA MOUNTAIN PEAKS USING GNSS MEASUREMENTS, MAPPING SERVICES, AND LIDAR DATA

STANOVENÍ VÝŠEK A HORIZONTÁLNÍCH POLOH VRCHOLŮ TATRÁCH POMOCÍ GNSS MĚŘENÍ, MAPOVACÍCH SLUŽEB A LIDAROVÝCH DAT

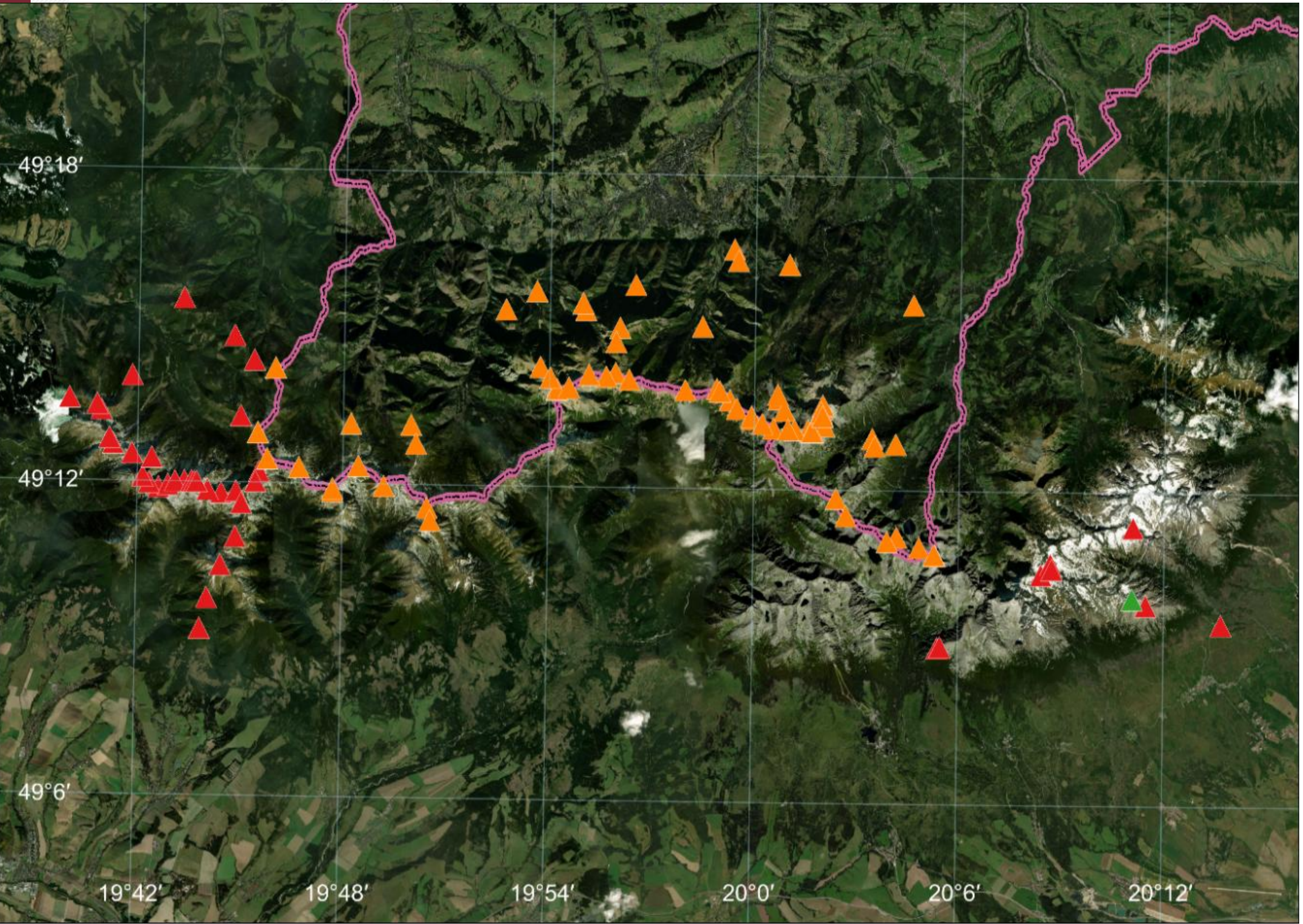
Dariusz Strugarek, Krzysztof Sośnica

Institute of Geodesy and Geoinformatics, Wrocław University of Environmental and Life Sciences (UPWr), Poland

Outline

1. GNSS measurement campaigns
2. LiDAR and mapping services
3. Data processing
4. GNSS vs LiDAR (height comparison)
5. GNSS vs maps (horizontal comparison)
6. Peaks and passes heights based only on LiDAR+maps
7. Summary and conclusions

GNSS measurement campaigns



- **Two campaigns in 2022 and 2024**
- **Precise GNSS measurements**: GPS/GLONASS/Galileo/BeiDou, RTN mode (ASG-EUPOS stations), LEICA & TRIMBLE receivers, acc. 2-3 cm horizontal, ~5 cm vertical
- Multiple sessions in location (3-5 x 5sec session)
- **12 people, 5 teams, 23 (14+9) days**
- **~800 measurements → 140 heights** of peaks (109), passes (31) incl. border pillars, etc.
- +static measurements on Slavkovský štít

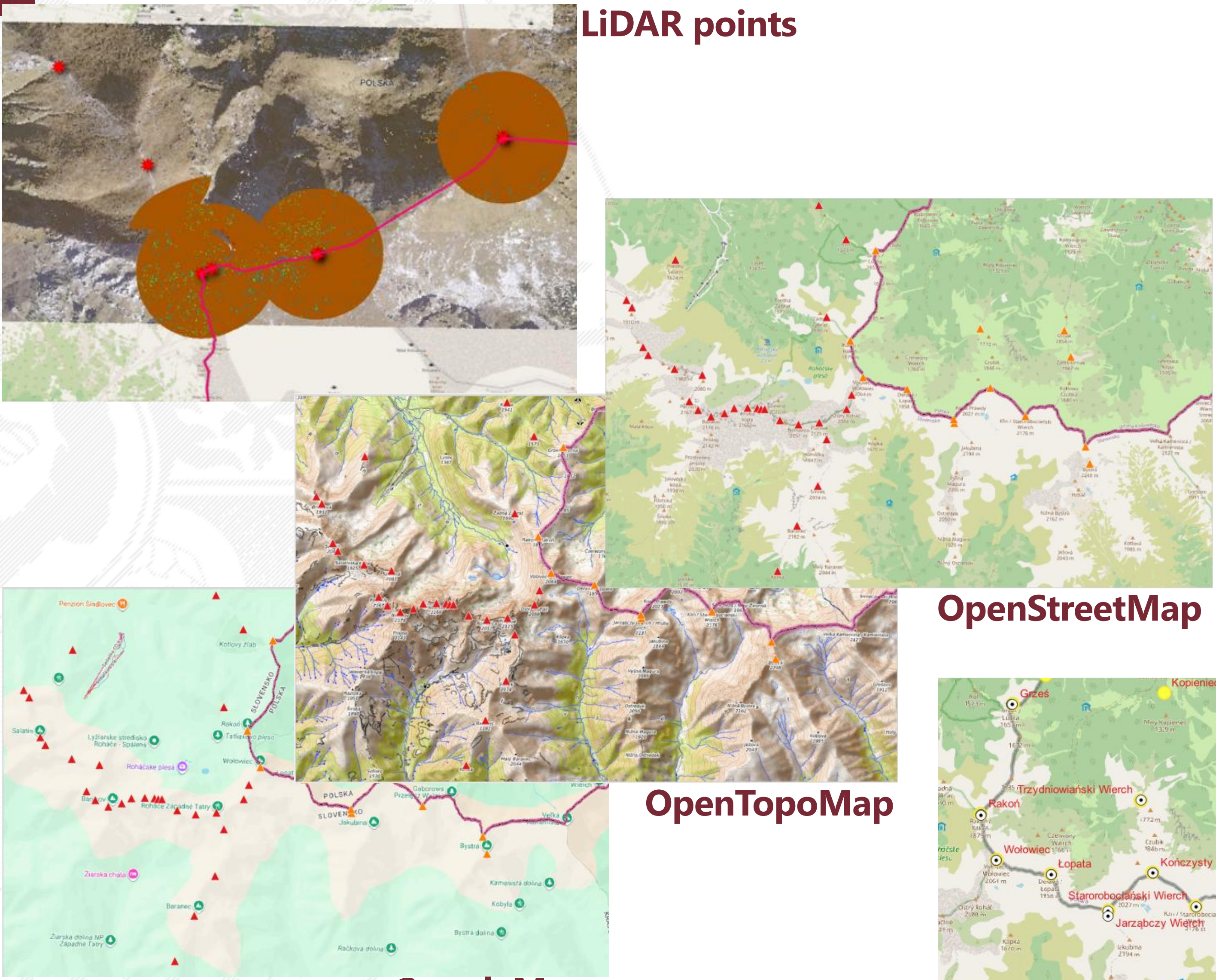
112 ‚natural' peaks & passes locations and heights,

confirmation/changes of height values:

Świnica: 2301 → 2302,36 m asl

M. Kozi Wierch: 2228 → 2225,53 m asl

LiDAR and mapping services



LiDAR points

OpenStreetMap

OpenTopoMap

GoogleMaps

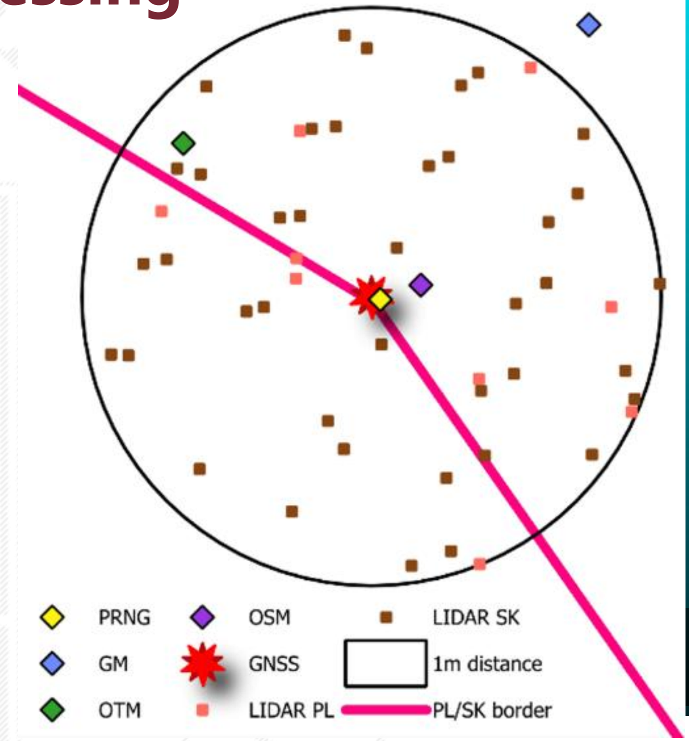
Two airborne LiDAR datasets used for Tatry region: PL LiDAR (2012) provided by GUGIK within ISOK project and **SK LiDAR** (2018), LOT26 Tatry Mračno bodov, provided by GKU, Bratislava – height information + horizontal location

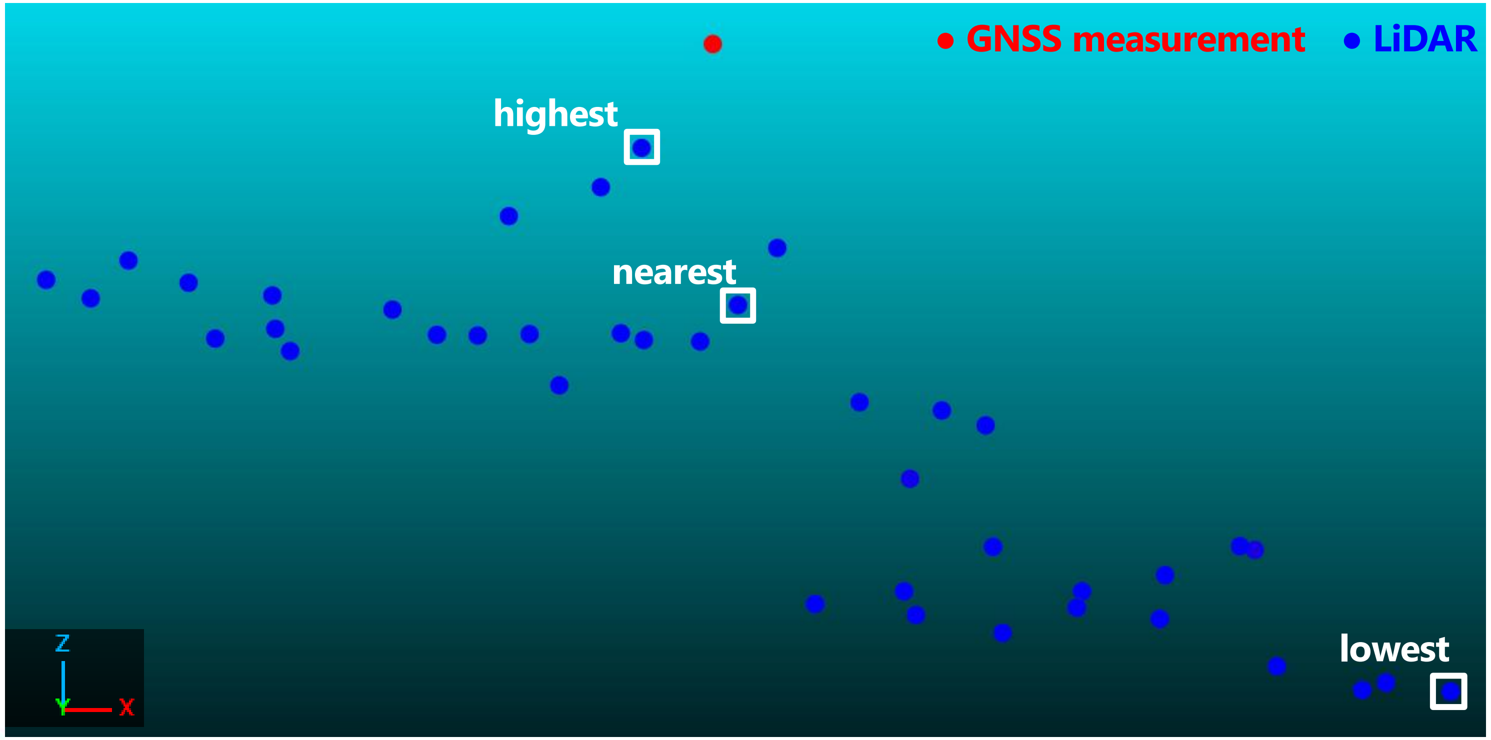
Map service data: OpenStreetMap (OSM), OpenTopoMap (OTM), GoogleMaps (GM) using WMS services allow for vectorization of peak locations – horizontal location (106 OSM, 104 OTM, 70 GM)

National Register of Geographical Names (PRNG) provided by GUGIK, geolocated names of geographic objects, and physiographic features incl. peaks and passes – horizontal location (66 objects – PL territory only)

PRNG

Data processing





GNSS data: transformation to unified frame GRS-80 (BLh), filtering and selection of ‚natural' peaks & passes

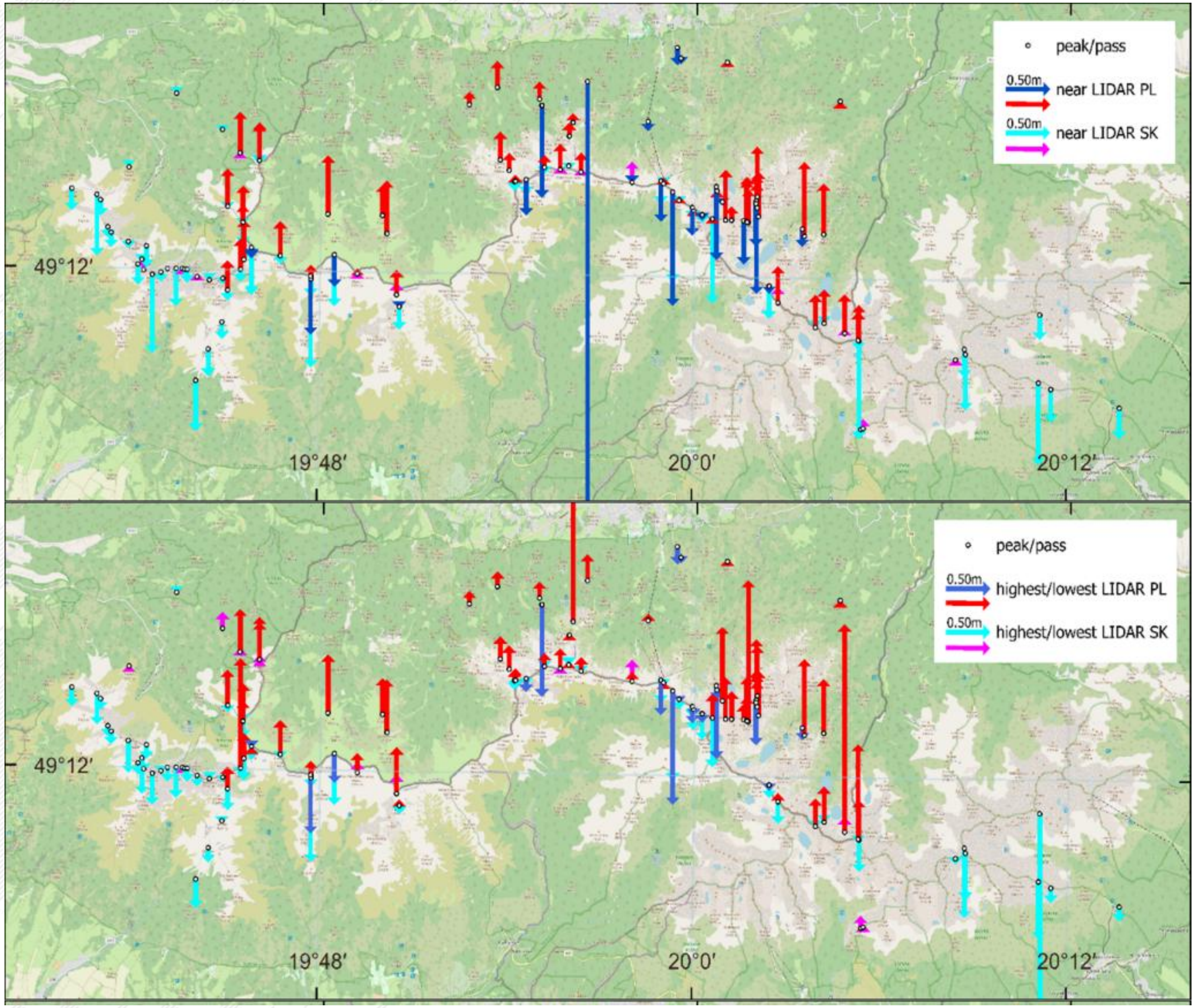
PL/SK LiDAR data: spatial selection within Tatra mountains, transformation to unified frame GRS-80, extraction of ground class (cl. 2) LiDAR points (BLh)

OSM/OTM/GM data: identification and vectorization of peaks & passes in GRS-80 frame (BL)

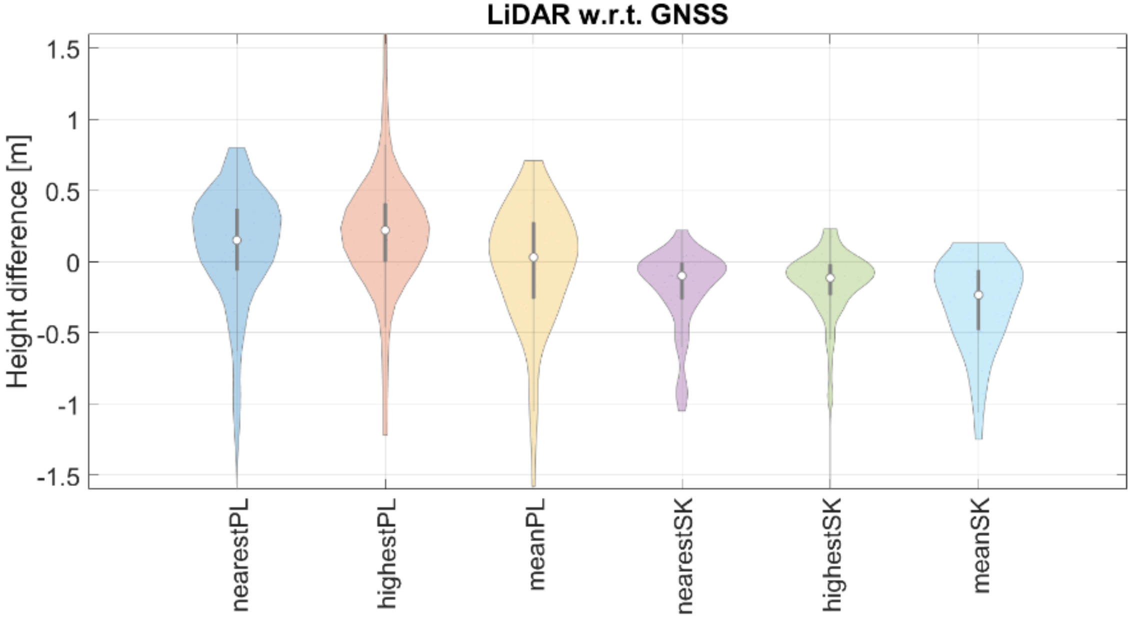
PRNG data: spatial selection within Tatra mountains, extractions of points representing peaks & passes, transformation to unified frame GRS-80

- Point selection approaches (for LiDAR clouds): **nearest point, highest point, lowest points, or mean height of points** within distance of 1m or 5m
- Deriving height and horizontal location, data comparison:
  GNSS vs LiDAR
  GNSS vs OSM/OTM/GM
  GNSS vs OSM/OTM/GM/PRNG+LiDAR

GNSS vs LiDAR for peaks and passes (height comparison - dh)



Spatial distribution of height differences between GNSS-measured and LiDAR-derived heights (top: nearest, bottom: highest approach)



Distributions of height differences between GNSS-measured and LiDAR-derived heights using the nearest, highest (for peaks) / lowest (for passes), and mean point selection approaches.

PL LiDAR dataset:

- all approaches exhibit positive bias (med.: 0.15, 0.26, 0.05m)

SK LiDAR dataset:

- all approaches exhibit negative bias (med.: -0.09,-0.04,-0.23m)

PL LiDAR has increased dispersion w.r.t. SK LiDAR

dh values are primarily explained by the LiDAR characteristics and height approach rather than by geographical location

No systematic N/S, E/W, or other spatial trends are evident

Positive (red) values indicate LiDAR-derived heights higher than GNSS, whereas negative (blue) indicate lower height than GNSS.

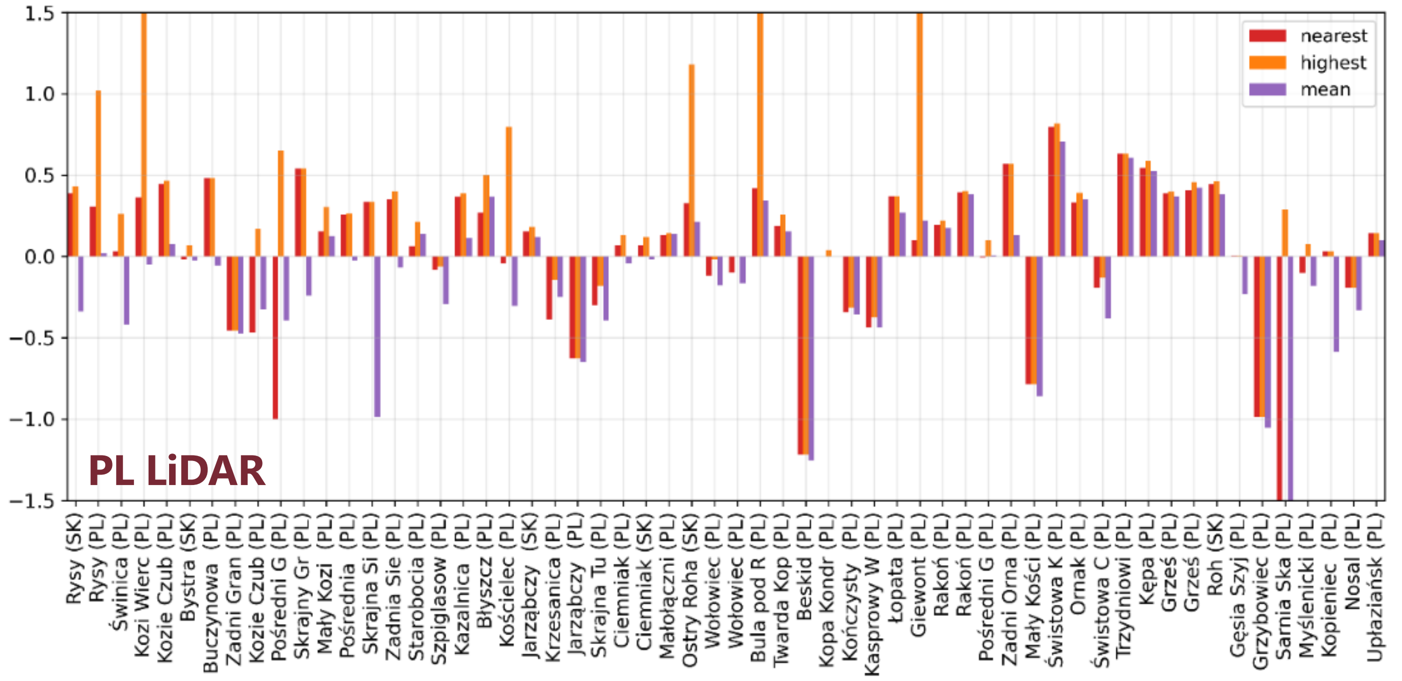
GNSS vs LiDAR for peaks (height comparison - dh)

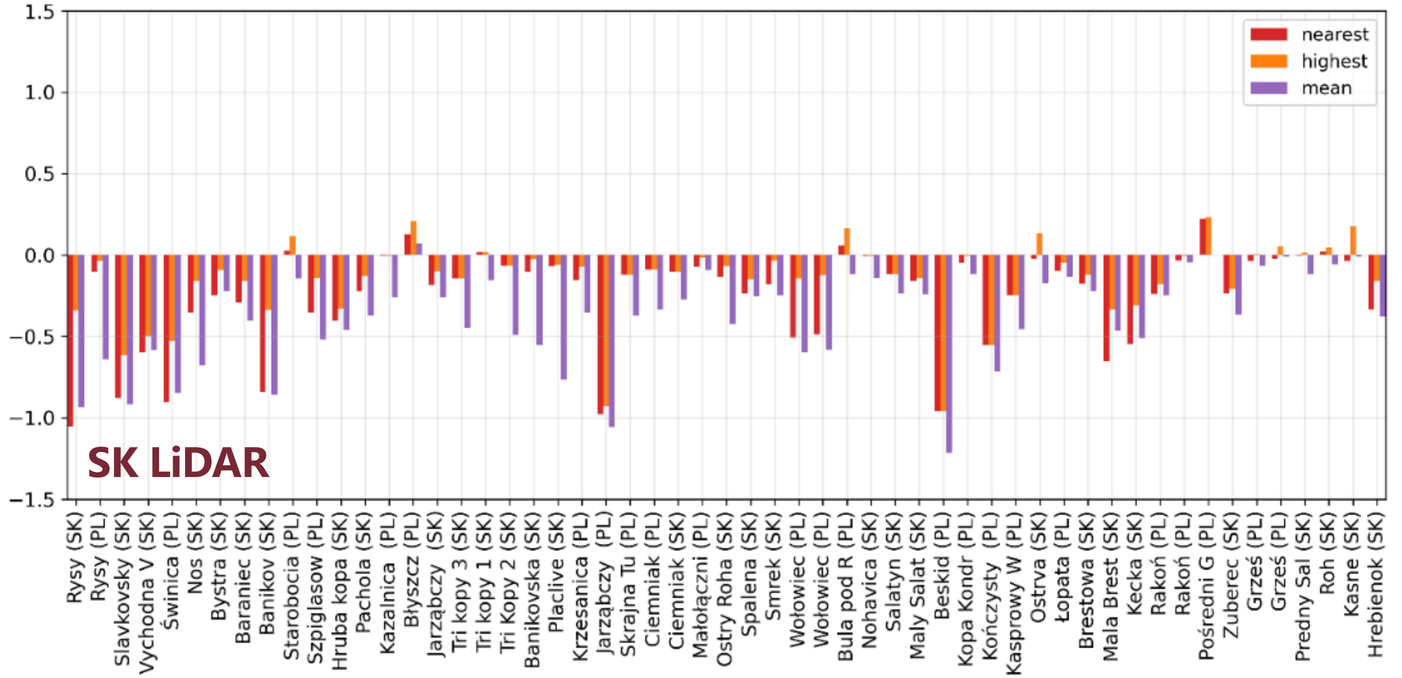
PL LiDAR dataset:

- most dh values within ±0.5m.
- nearest-point and highest-point approaches tend to yield more positive dh values, whereas the mean-point approach results in more negative dh values
- Giewont, Ostry Roháč, Kozi Wierch, and Bula pod Rysami peaks exhibit large positive dh values of 1 m or more
- Giewont – reflection from metal cross on peak. Sarnia Skała – high negative dh - the presence of near-vertical rock walls, laser returns from nearby lower surfaces

SK LiDAR dataset:

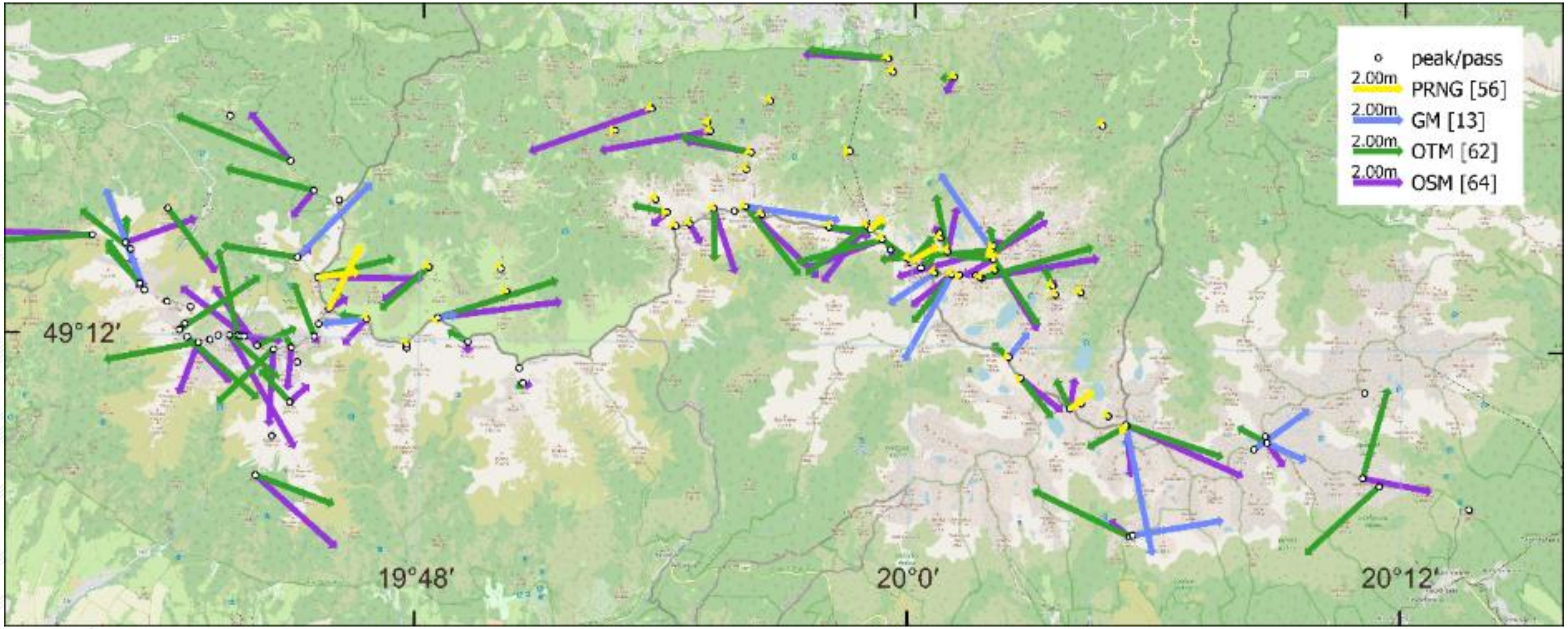
- dh are predominantly negative, with values within the range from 0 to −0.5 m
- mean-point method yields the most negative dh values, followed by the nearest-point and highest-point approaches





Height differences (dh, in m) between GNSS-measured and PL/SK LiDAR-derived peak heights for tested approaches

GNSS vs maps (horizontal comparison)



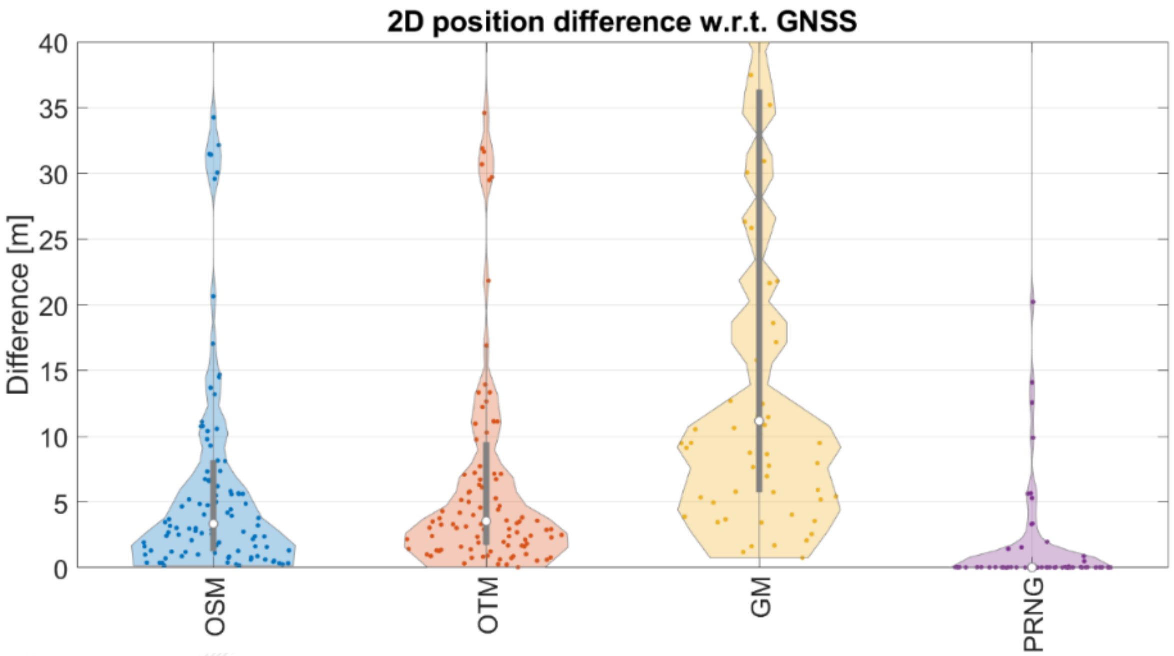
Horizontal displacement distance and direction between GNSS-measured locations and positions from PRNG and maps

Horizontal difference **> 20m**:

PRNG=4, OSM/OTM=14, GM=27

Horizontal difference **<5m:**

PRNG=56, OSM=64, OTM=62, GM=13



Distributions of 2D position differences between GNSS-measured peak and pass locations and positions from PRNG and maps

PRNG yields the lowest values with a median difference of 0.03 m

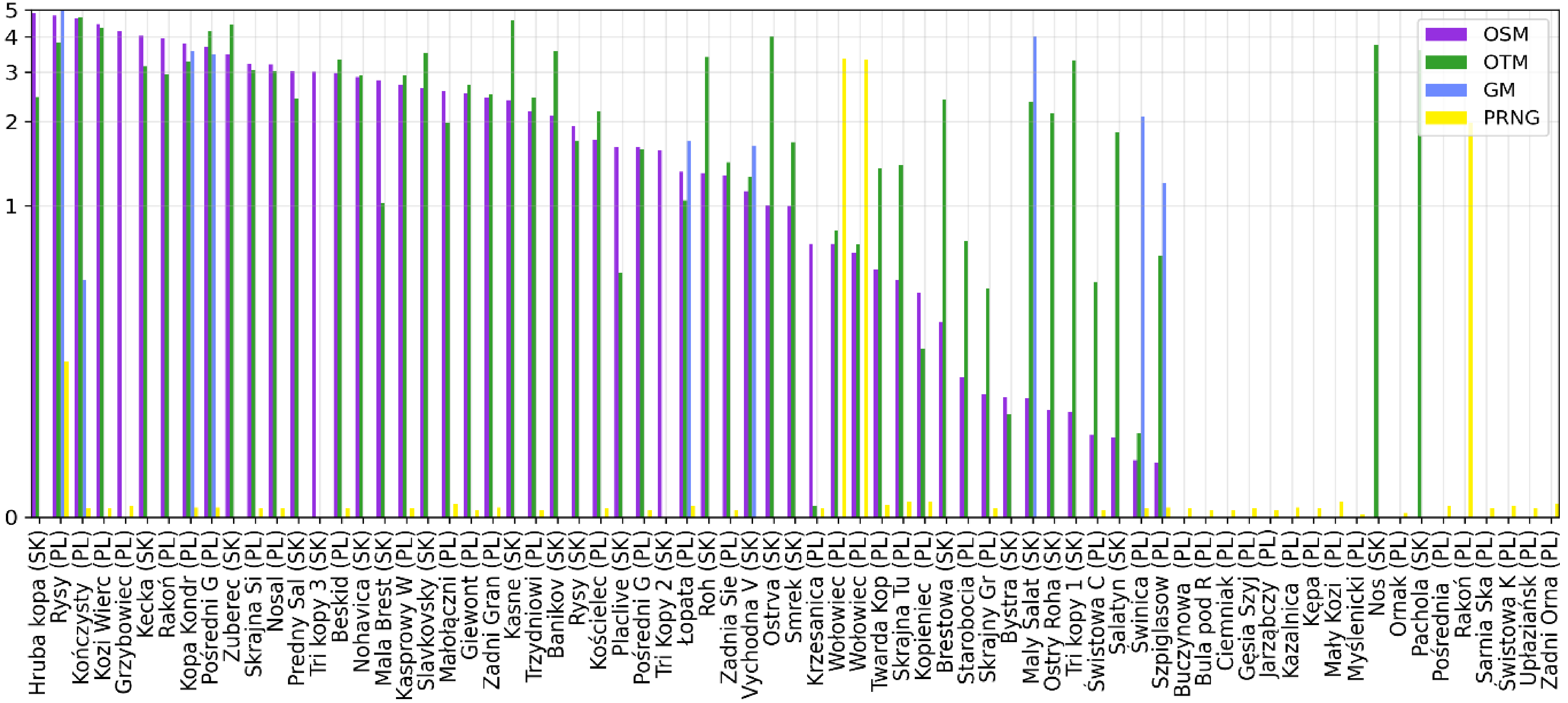
OSM and OTM show larger discrepancies, with median of ~3.6 m

GM dataset performs worst, with a median of 11.5 m

Random vector directions for all datasets, with no clear evidence of large-scale systematic shifts

OSM/OTM vectors exhibit partial directional agreement, possibly reflecting the use of similar underlying data sources

GNSS vs maps (horizontal comparison)

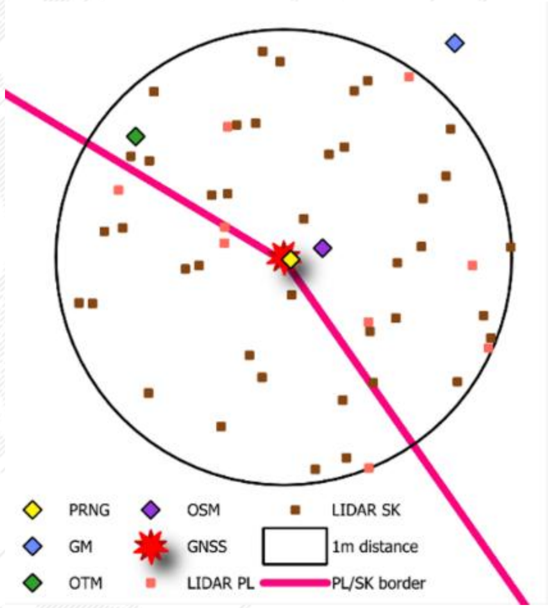


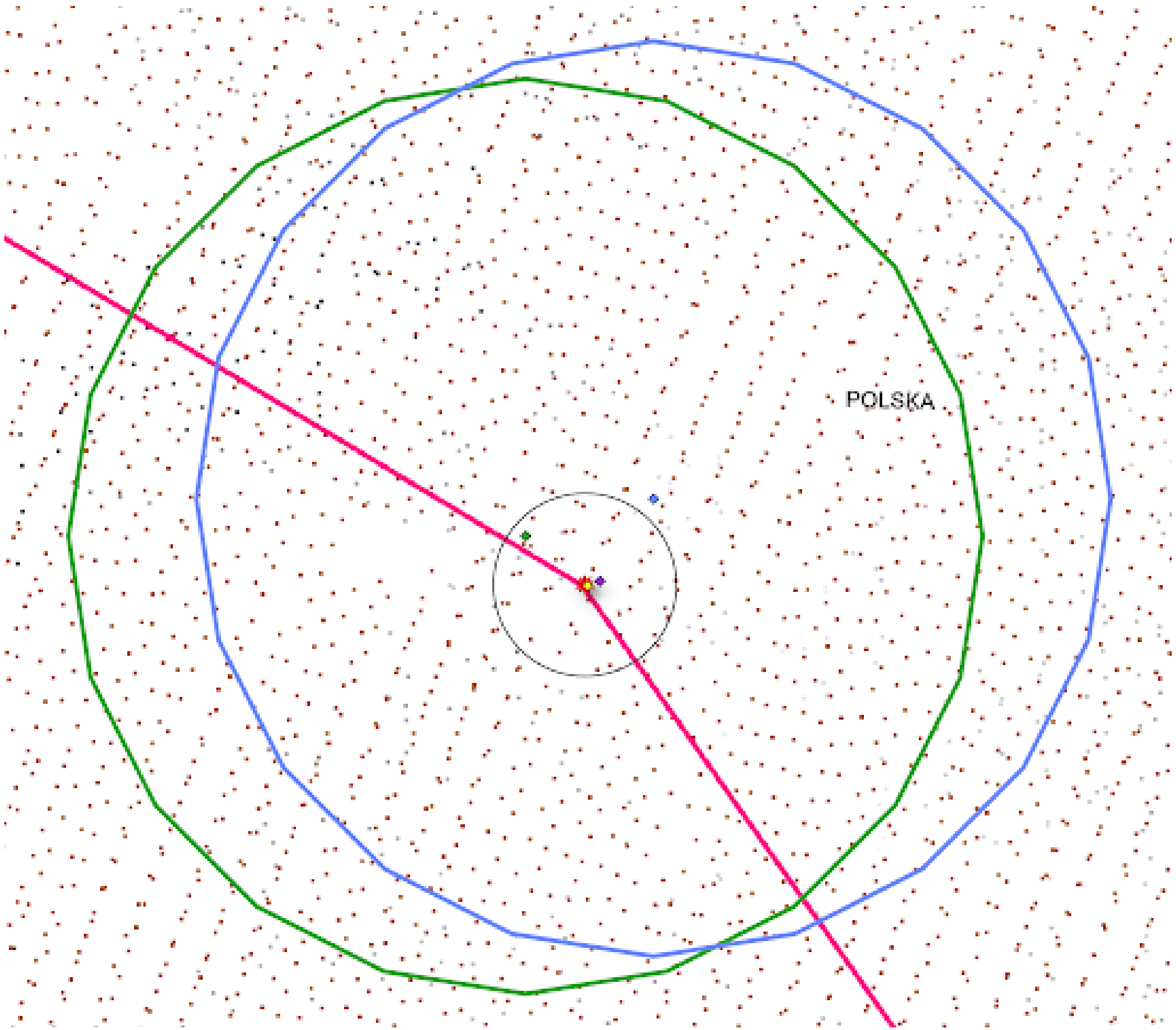
Distances between GNSS-measured locations and positions derived from PRNG, GM, OTM, and OSM mapping sources for peaks (distances larger than 5 m are omitted, in m).

Peaks and passes heights based only on LiDAR+maps

GNSS vs OSM/OTM/GM+LiDAR
GNSS vs PRNG+LiDAR

Based on horizontal comparison we changed search radius to 5m w.r.t. points from mapping sources





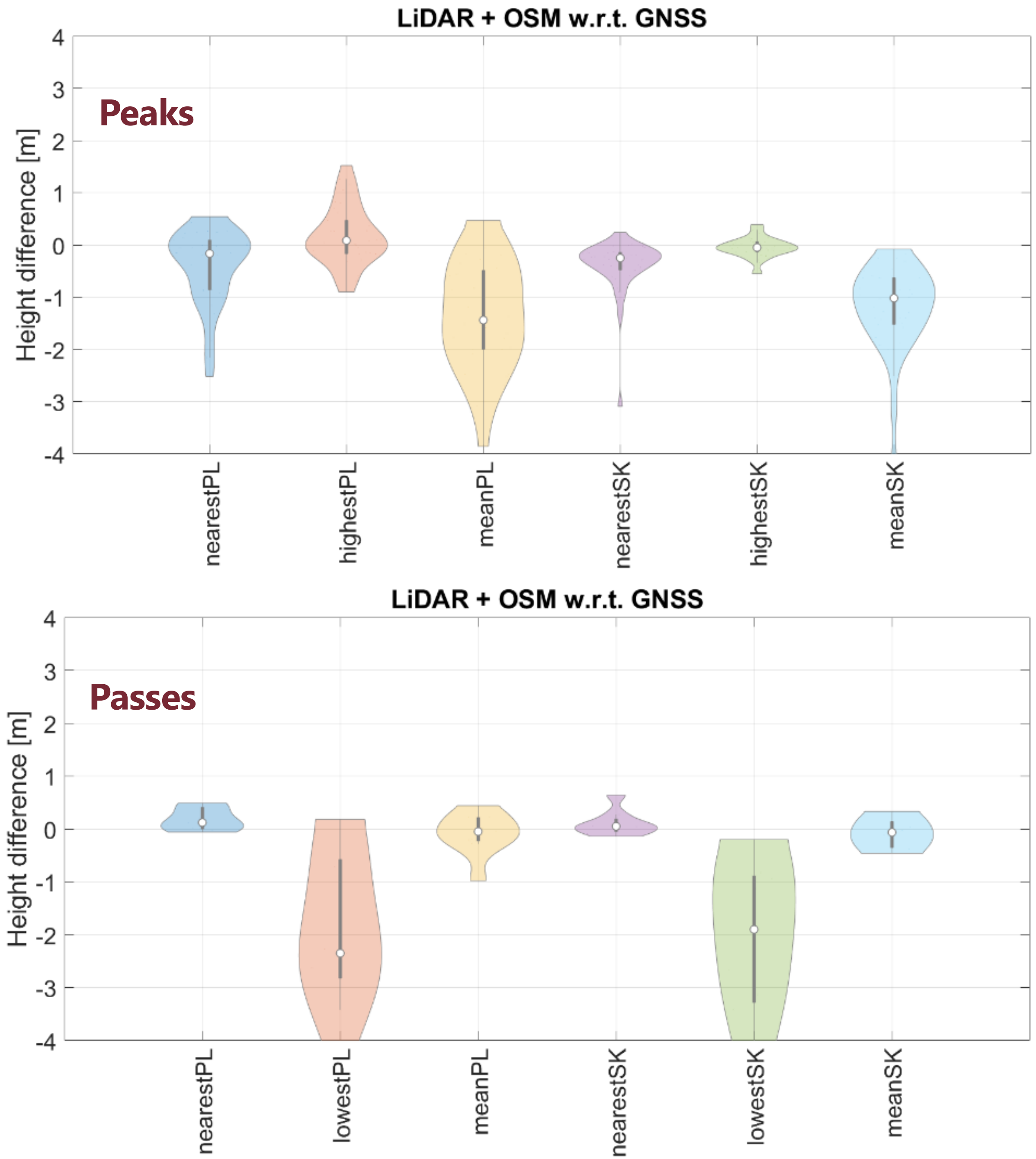
Peaks and passes heights based only on LiDAR+maps

GNSS vs OSM/OTM/GM+LiDAR
GNSS vs PRNG+LiDAR

All: nearest-point yields small mean biases for all datasets, with **mean dh from −0.09 to −0.25 m** and medians ~0 (std: 0.35–0.59m) highest-point: positive **biases (0.06–0.4m)** with higher std up to 0.8m, mean-point: ~1m (biases and std)

Peaks: nearest-point yields small negative biases, with mean dh values ranging from −0.18 to −0.35 m (medians ~0m), highest-point reduces the negative bias and has lower variability. Mean approach is the worst

Passes: nearest-point provides the most stable results, with mean dh values of 0.11–0.24 m range and low dispersion –std <0.25 m, mean-point yields dh values with median ~0, but with slight dispersion increase. Lowest-point is the worst



Distributions of height differences between GNSS-measured and LiDAR+OSM-derived heights (PL and SK) using the nearest, highest, lowest, and mean point selection approaches for peaks/passes

Summary and conclusions

1. **We provide precise GNSS measurements of 140 peaks and passes in the Tatra Mountains.** We validate heights, and horizontal positions derived LiDAR data (PL/SK) and mapping sources, and determine peak and pass heights using only remotely derived data (LiDAR+maps).
2. **Peak and pass height biases and dispersion differences relative to GNSS are identified for Polish and Slovak national LiDAR datasets.** The PL LiDAR shows small height offsets relative to GNSS of 0.01–0.30 m with variability (RMS) of 0.36–0.63 m, while the SK LiDAR has negative biases of −0.06 to −0.27 m with RMS of 0.20–0.40 m.
3. **Horizontal differences are characterized with offsets of ~0.26 m for PRNG, ~2 m for OSM/OTM, while GM performing poorest.**
4. **LiDAR data+horizontal positions (PRNG/ OSM) enable peak and pass heights derivation without GNSS.** The nearest-point approach yields mean height differences of −0.09 to −0.25 m, while the highest-point approach yields positive biases of 0.06–0.43 m and increased variability. **Peak and pass heights can be estimated with standard deviations below 0.5 and 0.3 m**, respectively
5. **Nearest-point and highest-point selection strategies provide the most effective LiDAR+map-based height estimates.**

The achieved decimeter-level consistencies exceed typical map-based height precision, demonstrating the suitability of this approach in LiDAR-covered mountainous regions.

Thank you for your attention!
Děkujeme za pozornost!

Wrocław University of Environmental and Life Sciences

IGiG

Members of the UPWr: **K. Kaźmierski, A. Kaczmarek, S. Porucznik, A. Nowak, M. Mikoś, F. Gałdyn, J. Najder, K. Smolak, and T. Kur** are acknowledged for participating in Tatra's peaks measurement campaigns. Campaigns were funded by the UPWr program for SPACEOS groups.

GUGiK is acknowledged for providing PL LiDAR and PRNG data. GKU is acknowledged for providing SK LiDAR data.

[1] Sośnica K, Strugarek D, Kaźmierski K, et al. (2023). The Crown of the Polish Mountains-geodetic measurement of the Tatras. Przegląd Geodezyjny. Vol. XCV, No. 7, 11-14. Warsaw

[2] Strugarek D., Sośnica K. (2026). Determining the heights and horizontal positions of Tatra Mountain peaks using GNSS measurements, mapping services, and LiDAR data. Measurement (under review)

[3] Strugarek D., Trojanowicz M., Mikoś M. et al. (2026). Height determination based on GNSS measurements in the mountainous area: contribution of the geoid model and data processing technique to the overall error budget. GPS Solutions (accepted).

dariusz.strugarek@upwr.edu.pl

Institute of Geodesy and Geoinformatics UPWr, Wrocław PL

This survey collects expert insight into the **implementation, use, and practical limitations of** national geodetic **reference frames**, CORS, and vertical datums. Completing the questionnaire takes **~10 min.** Your input will contribute to the base used by ESA to support improvements in geodetic reference frames.

E-NAFF
Exploring the Needs for Accurate reFerence Frames

Wrocław University of Environmental and Life Sciences

Shaping the Future of European Reference Frames – E-NAFF Survey

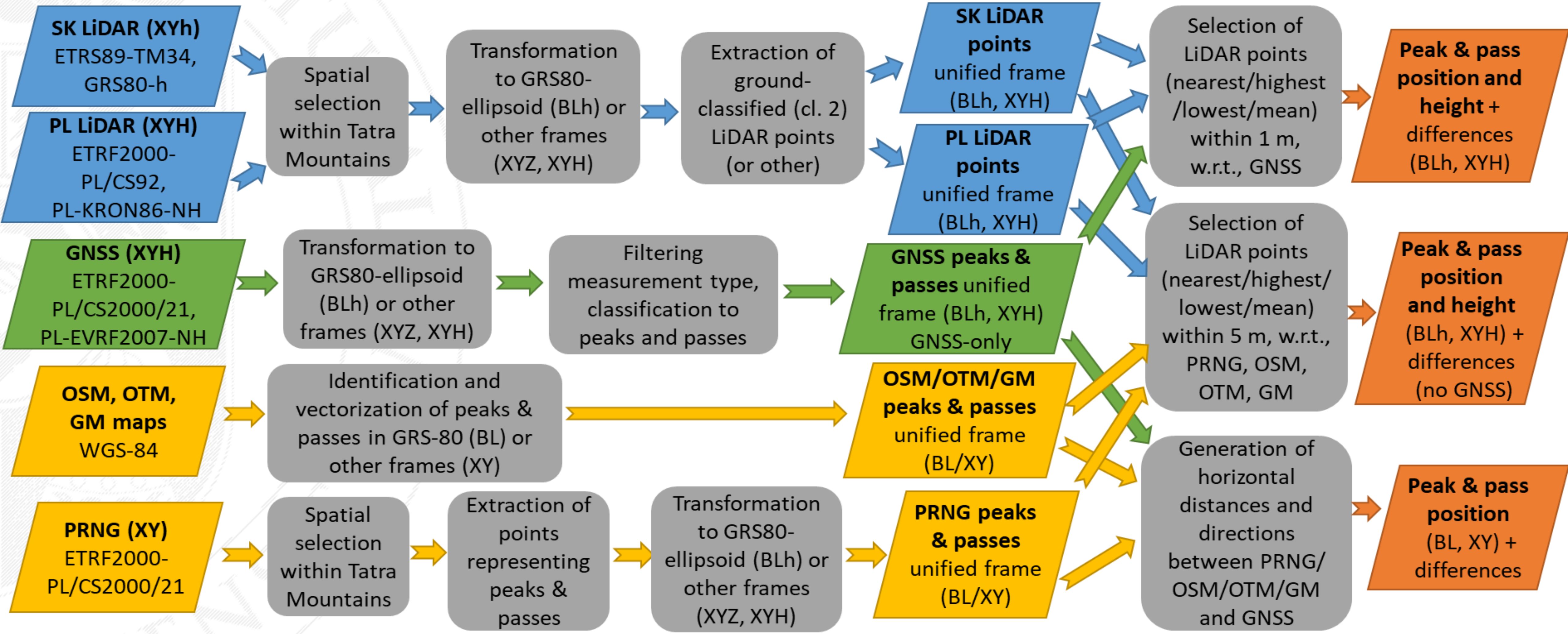
Geodetic reference frames are a critical foundation for high-precision positioning and GNSS-based applications across Europe.

RTN, PPP vs static GNSS measurements on Slavkovský štít

Solution	Technique	Data	Type	Time	Software	Height [m]
ASG-EUPOS 1	RTN/VRS	real-time	differential	beginning	TPP	2452.532
ASG-EUPOS 2	RTN/VRS	real-time	differential	beginning	TPP	2452.532
ASG-EUPOS 3	RTN/VRS	real-time	differential	beginning	TPP	2452.529
ASG-EUPOS 4	RTN/VRS	real-time	differential	end	TPP	2452.545
PPP-C	PPP	RINEX	absolute	2h	CSRS	2452.521
PPP-W	PPP	RINEX	absolute	2h	WARP	2452.524
RTK-L	RTK/tropo	RINEX	differential	2h	RTKLib	2452.540
RTK-T*	RTK/no tropo	RINEX	differential	2h	RTKLib	2452.370
Static	DD	RINEX	differential	2h	Bernese	2452.521

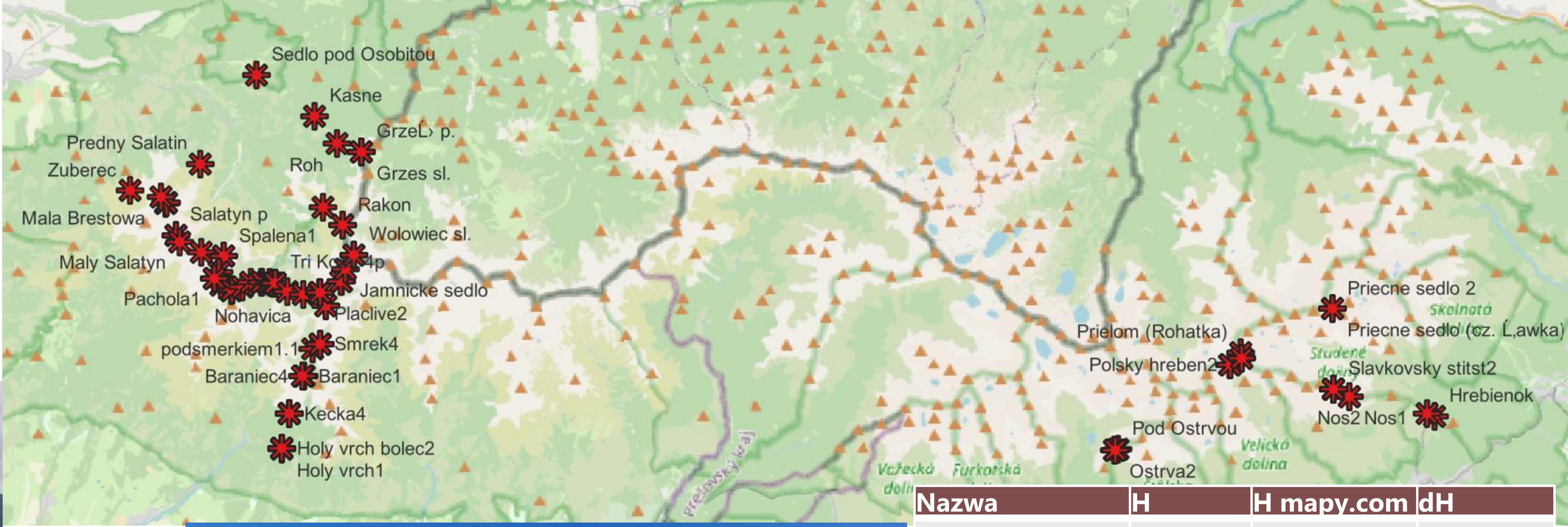
Characteristics of the different GNSS data processing techniques and the resulting heights provided w.r.t. the Quasigeoid(PL) model for the Slavkovský štít. For RTK solutions, the NWT1 (Nowy Targ) GNSS station at a height of 614.082 m is used as a reference station.

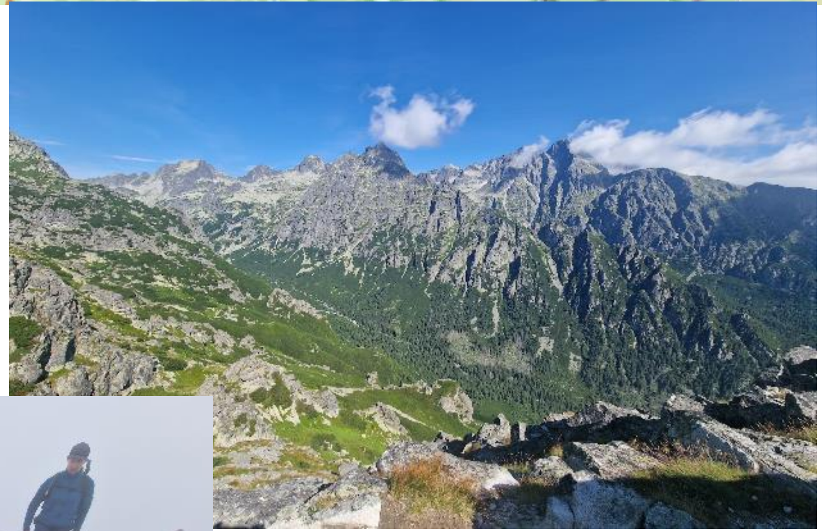
Distributions of height differences between GNSS-measured and LiDAR+OSM-derived heights (PL and SK datasets) using the nearest, highest, and mean point selection approaches for peaks/passes


SK LiDAR (XYh) ETRS89-TM34, GRS80-h
PL LiDAR (XYH) ETRF2000-PL/CS92, PL-KRON86-NH
Spatial selection within Tatra Mountains
Transformation to GRS80-ellipsoid (BLh) or other frames (XYZ, XYH)
Extraction of ground-classified (cl. 2) LiDAR points (or other)
SK LiDAR points unified frame (BLh, XYH)
PL LiDAR points unified frame (BLh, XYH)
Selection of LiDAR points (nearest/highest /lowest/mean) within 1 m, w.r.t., GNSS
Peak & pass position and height + differences (BLh, XYH)
GNSS (XYH) ETRF2000-PL/CS2000/21, PL-EVRF2007-NH
Transformation to GRS80-ellipsoid (BLh) or other frames (XYZ, XYH)
Filtering measurement type, classification to peaks and passes
GNSS peaks & passes unified frame (BLh, XYH) GNSS-only
Selection of LiDAR points (nearest/highest/ lowest/mean) within 5 m, w.r.t., PRNG, OSM, OTM, GM
Peak & pass position and height (BLh, XYH) + differences (no GNSS)
OSM, OTM, GM maps WGS-84
Identification and vectorization of peaks & passes in GRS-80 (BL) or other frames (XY)
OSM/OTM/GM peaks & passes unified frame (BL/XY)
Generation of horizontal distances and directions between PRNG/ OSM/OTM/GM and GNSS
Peak & pass position (BL, XY) + differences
PRNG (XY) ETRF2000-PL/CS2000/21
Spatial selection within Tatra Mountains
Extraction of points representing peaks & passes
Transformation to GRS80-ellipsoid (BLh) or other frames (XYZ, XYH)
PRNG peaks & passes unified frame (BL/XY)

Sarnia Skała, Giewont

Kampania Pomiarowa w Tatrach Słowackich

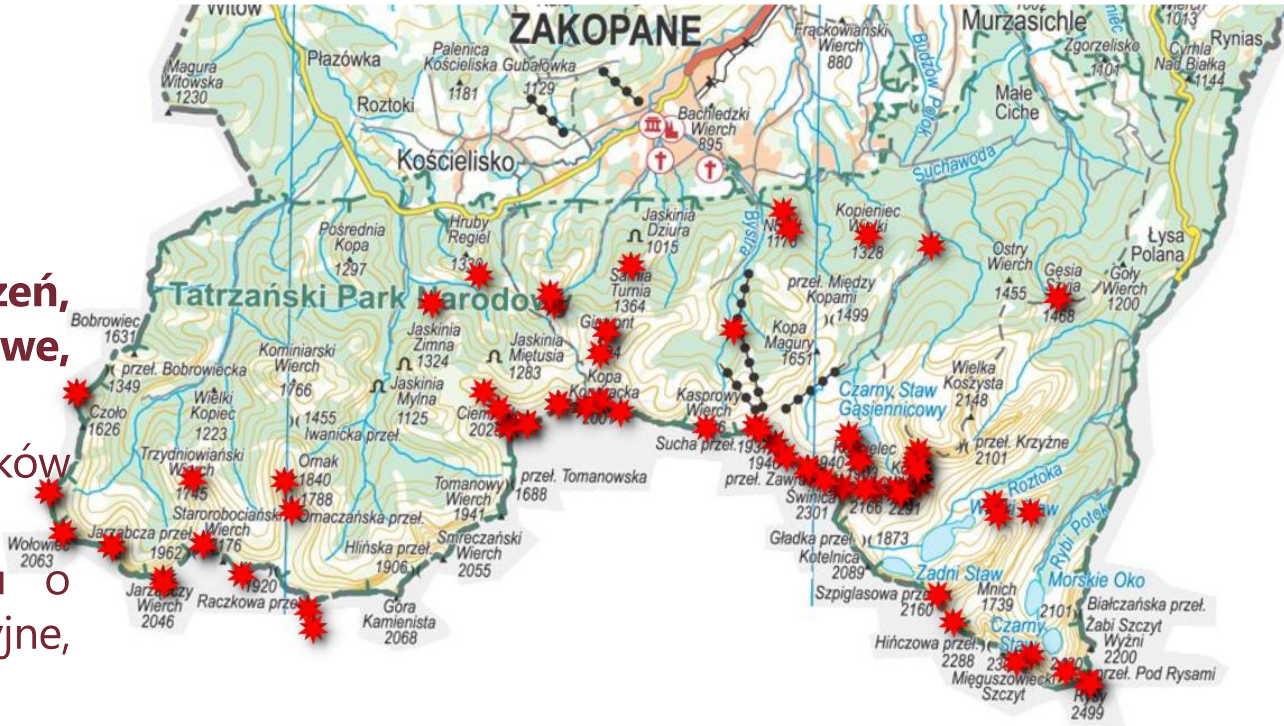




Nazwa	H	H mapy.com	dH
Priecne sedlo	2311,35	2352	40.65
Hrebienok	1261,45	1285	23.55
Lucne sedlo	2073,74	2060	-13.74
Predny Salatin	1634,38	1624	-10.38
Holy vrch1	1675,99	1683	7.01
Zuberec	1747,43	1753	5.57
Prielom (Rohatka)	2293,50	2288	-5.5
Mala Brestowa	1908,24	1903	-5.24
Sedlo Zabrat	1660,95	1656	-4.95
Banikovske sedlo	2043,41	2040	-3.41
Jamnicke sedlo	1911,25	1908	-3.25
Ostrva	1981,42	1984	2.58
Spalene Sedlo	2052,51	2055	2.49
Sedlo pod Osobitou	1523,25	1521	-2.25
Smrek	2071,96	2074	2.04
Polsky hreben	2201,77	2200	-1.77
Hruba kopa	2167,69	2166	-1.69
Pod Ostrvou	1967,65	1966	-1.65
Ostry Rohac	2086,48	2088	1.52
Nohavica	2049,58	2051	1.42
Ziarskie sedlo p	1915,82	1917	1.18

Kampania pomiarowa UPWr

- **232 km szlaków, 39963 m sumy przebytych przewyższeń, 10 osób, 3 zespoły pomiarowe, ~2 tygodnie**
- **570 pomiarów → 82 wysokości** szczytów, przełęczy, słupków granicznych.
- wykorzystano **infrastrukturę IGIG,** pomiary w oparciu o obserwacje GNSS (GPS, GLONASS, Galileo i BeiDou), precyzyjne, wieloczęstotliwościowe **odbiorniki LEICA, TRIMBLE**



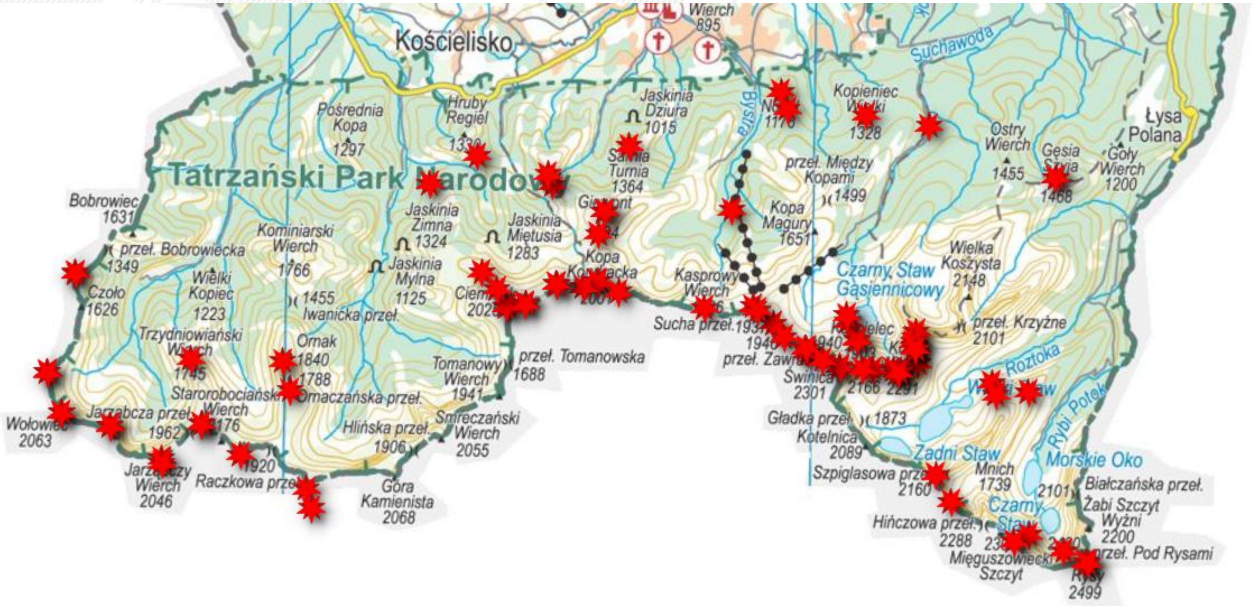
- wykorzystanie poprawek generowanych przez ASG-EUPOS oraz o poprawki sieciowe czasu rzeczywistego (RTN) w oparciu o stacje referencyjne na terenie Polski i Słowacji, pomiar w układzie współrzędnych płaskich 2000/21
- wysokości elipsoidalne zostały zredukowane do systemu wysokości „Amsterdam", czyli **PL-EVRF2007-NH w oparciu o nowy model PL-geoid2021 (UPWr, IGIG),** dokładność 1,9 cm
- zakładany **błąd wyznaczenia wysokości wynosi nie więcej niż 5 cm** z wykorzystaniem korekt sieciowych RTN (NAWGEO) z uwzględnieniem dokładności modelu geoidy
- finansowanie: WZB SpaceOS

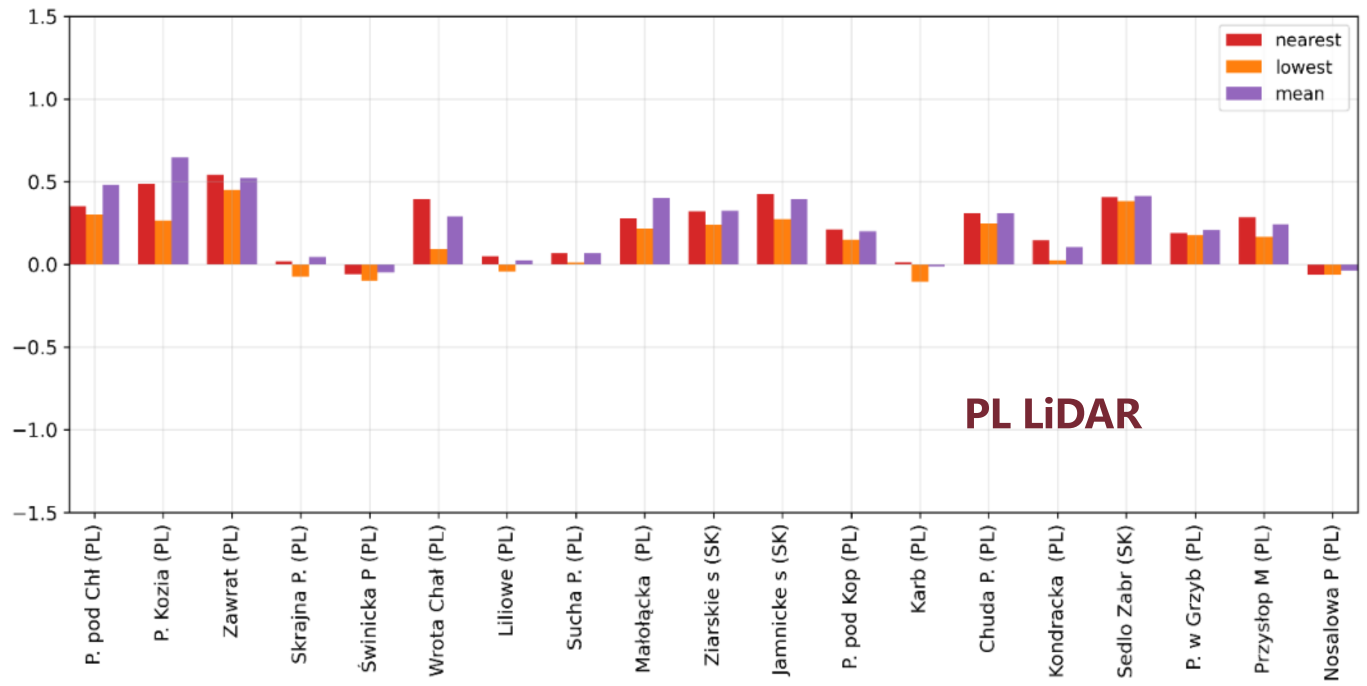
Jak wyglądał pomiar i porównanie wyników

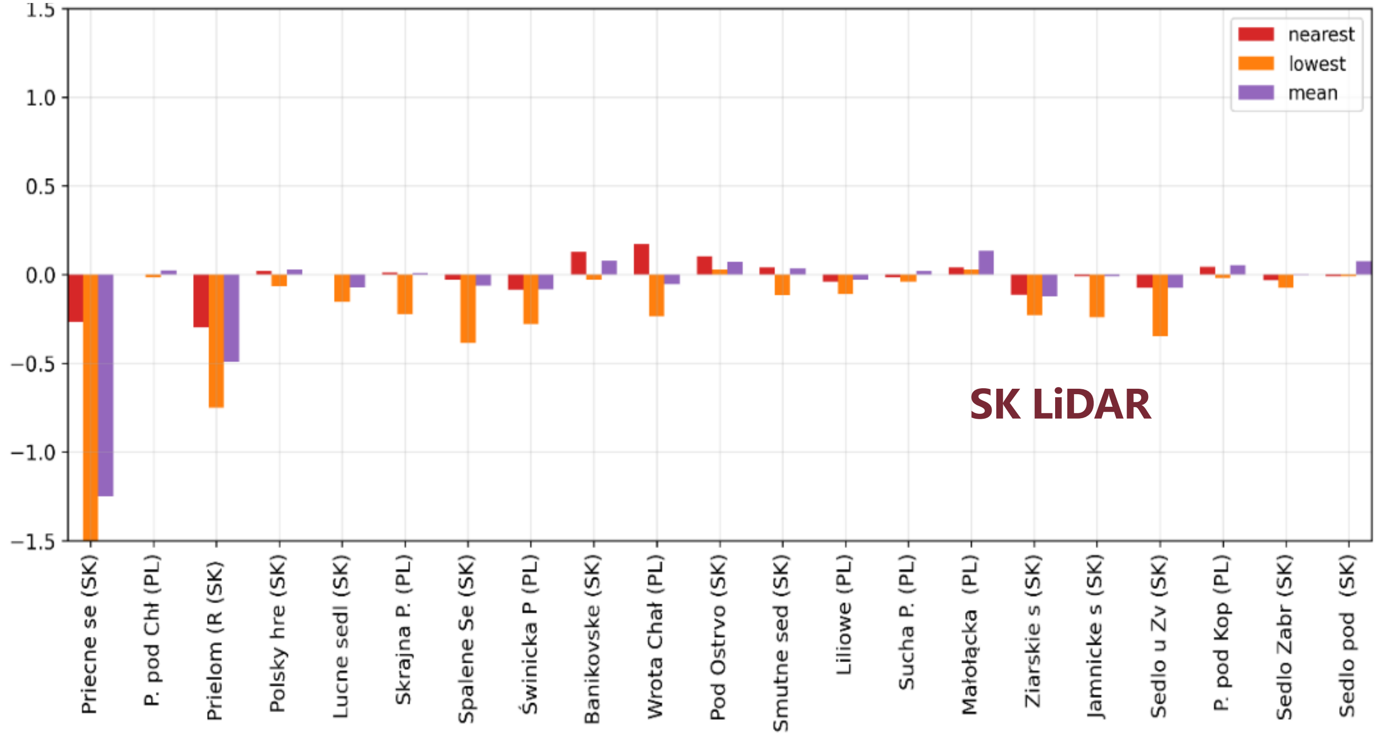
- jako szczyty, przełęcze czy punkty charakterystyczne przyjęto punkty pomiarowe charakteryzujące się **najwyższymi wysokościami, wypłaszczone miejsca przełęczy**, reprezentujące naturalną rzeźbę terenu, **nieruchome fragmenty skał, poziom gruntu,** lub **miejsca pod słupkami informacyjnymi** oraz **słupki graniczne,**
- kilkukrotny pomiar (3-5) w 5-sekundowych sesjach → uśrednienie wyników
- weryfikacja wyników względem danych z **krajowego geopo rtalu** (geoportal.gov.pl), **geoportalu tatrzańskiego** (gis.tpn.pl/portal), serwisów turystycznych i mapowych (**mapa-turystyczna.pl, Mapy.cz, openstreetmap.org, googlemaps.com, osmand.net**), map analogowych

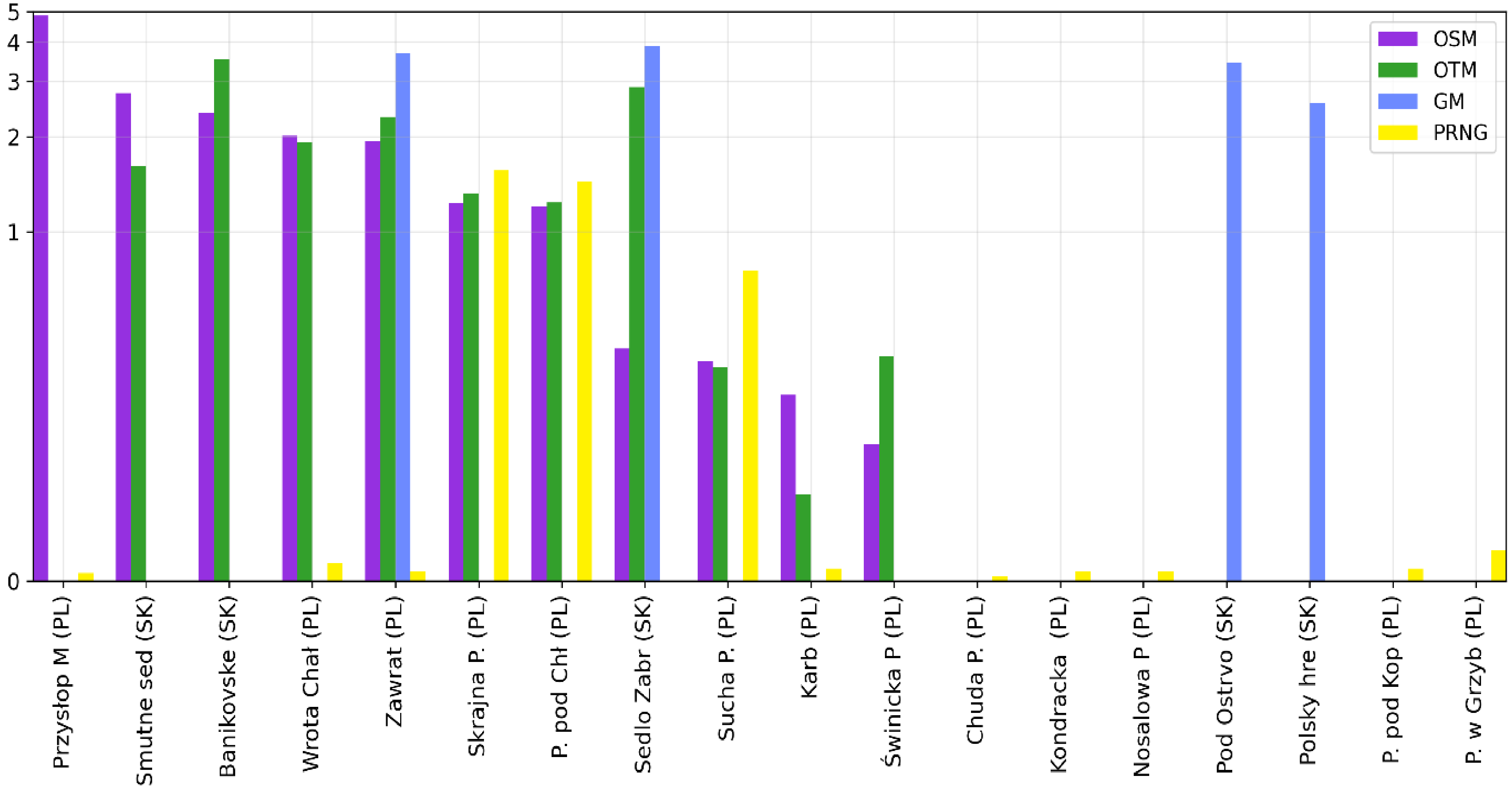
Kampania pomiarowa UPWr - wyniki

Wysokość m n.p.m.	dotychczasowa	pomierzona	różnica
Świnica	2301	2302,36	1,36
Mały Kozi Wierch	2228	2225,53	-2,47
Pośredni Granat	2234	2233,07	-0,93
Skrajny Granat	2225	2228,35	3,35
Bula pod Rysami	2054	2054,90	0,90
Rysy (cz. polska)	2499	2499,44	0,44
Rysy (cz. słowacka)	2503	2500,91	-2,09
Sarnia skała	1377	1377,97	0,97
Kopa Kondracka	2005	2004,20	-0,80
Krzesanica	2122	2122,59	0,59
Ciemniak	2096	2096,51	0,51




nearest
lowest
mean
PL LiDAR
P. pod Chł (PL)
P. Kozia (PL)
Zawrat (PL)
Skrajna P. (PL)
Świnicka P (PL)
Wrota Chał (PL)
Liliowe (PL)
Sucha P. (PL)
Małołącka (PL)
Ziarskie s (SK)
Jamnicke s (SK)
P. pod Kop (PL)
Karb (PL)
Chuda P. (PL)
Kondracka (PL)
Sedlo Zabr (SK)
P. w Grzyb (PL)
Przysłop M (PL)
Nosalowa P (PL)


nearest
lowest
mean
SK LiDAR
Priecne se (SK)
P. pod Chł (PL)
Prielom (R (SK)
Polsky hre (SK)
Lucne sedl (SK)
Skrajna P. (PL)
Spalene Se (SK)
Świnicka P (PL)
Banikovske (SK)
Wrota Chał (PL)
Pod Ostrvo (SK)
Smutne sed (SK)
Liliowe (PL)
Sucha P. (PL)
Małołącka (PL)
Ziarskie s (SK)
Jamnicke s (SK)
Sedlo u Zv (SK)
P. pod Kop (PL)
Sedlo Zabr (SK)
Sedlo pod (SK)



5
4
3
2
1
0
OSM
OTM
GM
PRNG
Przysłop M (PL)
Smutne sed (SK)
Banikovske (SK)
Wrota Chał (PL)
Zawrat (PL)
Skrajna P. (PL)
P. pod Chł (PL)
Sedlo Zabr (SK)
Sucha P. (PL)
Karb (PL)
Świnicka P (PL)
Chuda P. (PL)
Kondracka (PL)
Nosalowa P (PL)
Pod Ostrvo (SK)
Polsky hre (SK)
P. pod Kop (PL)
P. w Grzyb (PL)

Table 4. Statistics of height differences between GNSS measurements and PRNG +PL SK LiDAR-derived, and OSM+PL, SK LiDAR-derived heights after removing outliers (in m).

dh (LiDAR+map) - GNSS [m]	approach	mean	median	mean abs. dev.	st. dev.	rms	count (outliers)
PL PRNG	nearest	-0.09	0.07	0.45	0.59	0.59	55 (1)
	highest	0.43	0.29	0.55	0.70	0.82	55 (1)
	mean	-0.92	-0.81	0.79	0.91	1.28	54 (2)
SK PRNG	nearest	-0.24	-0.11	0.30	0.37	0.44	24 (0)
	highest	0.08	-0.04	0.33	0.46	0.46	23 (1)
	mean	-1.04	-0.99	0.61	0.76	1.27	24 (0)
PL OSM	nearest	-0.19	-0.03	0.42	0.54	0.57	41 (0)
	highest	0.42	0.26	0.60	0.76	0.86	43 (0)
	mean	-1.02	-0.85	0.84	0.97	1.40	42 (1)
SK OSM	nearest	-0.25	-0.22	0.25	0.35	0.42	46 (1)
	highest	0.06	-0.02	0.25	0.37	0.37	45 (2)
	mean	-0.90	-0.87	0.54	0.66	1.11	45 (2)

Table 5. Statistics of height differences between GNSS measurements and PRNG +PL SK LiDAR-derived, and OSM+PL, SK LiDAR-derived heights for peaks and passes after removing outliers (in m).

dh (LiDAR+map) - GNSS [m]	type	approach	mean	median	mean abs. dev.	st. dev.	rms	count (outliers)
PL PRNG	peak	nearest	-0.18	-0.01	0.49	0.63	0.65	43 (1)
		highest	0.18	0.13	0.38	0.49	0.52	43 (1)
		mean	-1.17	-1.43	0.73	0.85	1.44	42 (2)
SK PRNG	peak	nearest	-0.33	-0.25	0.30	0.36	0.48	19 (0)
		highest	-0.10	-0.07	0.13	0.19	0.21	19 (0)
		mean	-1.27	-1.10	0.54	0.65	1.42	19 (0)
PL PRNG	pass	nearest	0.24	0.20	0.17	0.22	0.32	12 (0)
		lowest	-1.40	-1.35	0.97	1.09	1.74	11 (1)
		mean	0.06	0.05	0.18	0.21	0.21	11 (1)
SK PRNG	pass	nearest	0.13	0.17	0.07	0.08	0.14	5 (0)
		lowest	-2.67	-2.85	1.66	2.36	3.40	5 (0)
		mean	-0.14	0.00	0.26	0.30	0.30	5 (0)
PL OSM	peak	nearest	-0.35	-0.15	0.51	0.64	0.72	33 (1)
		highest	0.18	0.08	0.44	0.57	0.59	34 (0)
		mean	-1.35	-1.44	0.84	1.01	1.67	34 (0)
SK OSM	peak	nearest	-0.33	-0.25	0.24	0.32	0.45	38 (1)
		highest	-0.04	-0.05	0.13	0.18	0.19	38 (1)
		mean	-1.13	-1.01	0.53	0.67	1.31	38 (1)
PL OSM	pass	nearest	0.19	0.12	0.18	0.22	0.28	9 (0)
		lowest	-2.41	-2.35	1.49	2.36	3.28	9 (0)
		mean	-0.09	-0.05	0.29	0.41	0.40	9 (0)
SK OSM	pass	nearest	0.11	0.05	0.17	0.25	0.26	8 (0)
		lowest	-2.35	-1.90	1.57	2.04	3.02	8 (0)
		mean	-0.09	-0.06	0.23	0.29	0.28	8 (0)