A Novel Solution To Validate GNSS Receiver For Autonomous Driving (VaGAD)

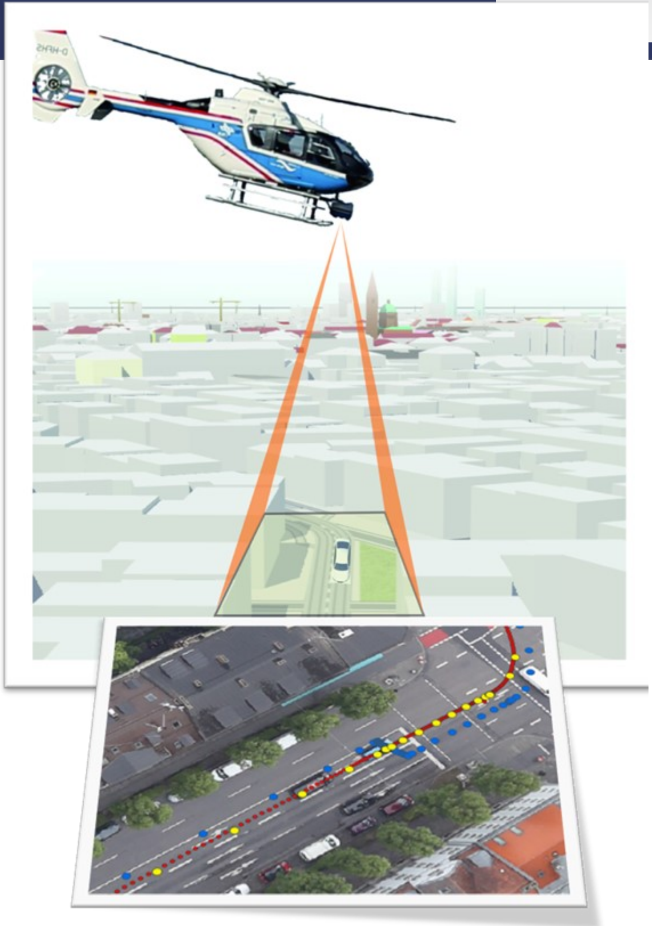
A NAVISP Element 2 Project

Paulo Mendes & Franz Kurz, 18th of January 2022

Agenda

Webinar agenda:

- NavCert & DLR EOC profiles
- VaGAD Project Context
- Certification & Validation
- VaGAD Method
- VaGAD Test Campaign
- VaGAD Analysis & Results
- Conclusions



VaGAD Webinar

NavCert Profile

Provides independent testing, validation and certification of GNSS components, products, solutions and services.

The NavCert GmbH was founded as a Joint Venture between TÜV Süd and OECON in 2006.

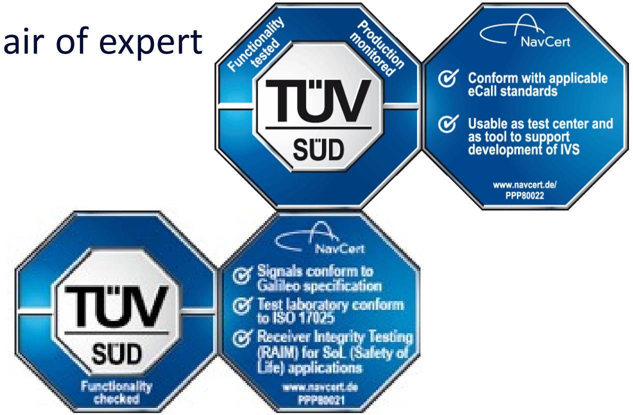
Since 2012 NavCert GmbH is a 100% subsidiary of the OECON Holding GmbH.

The only laboratory in Europe accredited by a national accreditation Authority in the domain of GNSS.

Notified Body (NB 2603) for European Electronic Tolling Service and Chair of expert groups EETS.

Provides certification:

- eCall - first eCall type approval in Europe
- GNSS solutions, GNSS testbed systems (e.g., GATE), Digital Maps
- UAS
- EETS, ….



NavCert Profile

Participates in national and EU projects (GNSS/AD/RAILWAY/NextGen-eCall)

- ACCURATE (EU)
- CLUG (EU)
- GEARS (EU)
- SAFE (EU)
- GHOST HUNTER (National)
- SynCoPark (National)
- VEREDUS (National)

Based in Braunschweig & Munich.

Member of DIN and ETSI standardization organisations and delegated expert at DIN, CEN/CENELEC and ISO.


DAkkS Deutsche Akkreditierungsstelle

Deutsche Akkreditierungsstelle GmbH

Anlage zur Akkreditierungsurkunde D-PL-17052-01-00
nach DIN EN ISO/IEC 17025:2018

Gültig ab: 13.08.2021
Ausstellungsdatum: 13.08.2021

Urkundeninhaber:
NavCert GmbH
Hermann-Blenk-Straße 22a, 38108 Braunschweig

am Standort:
Schwanthaler Straße 14, 80336 München

Prüfungen in den Bereichen:
GNSS basierte Flächenmesssysteme, Geräte und Systeme zur Messung von geodätischen Koordinaten;
Intelligente Transport Systeme - eSafety und eCall; Technische Prüfungen von bordeigenen eCall-Systemen, selbstständigen technischen Einheiten und Bauteilen nach Verordnung (EU) 2017/79 (hier: Annex I, II, III, IV, V, VI, VII, VIII);
Prüfen und Messen innerhalb der Module A1, A2, B, C1, C2, F, F1, G des Europäischen elektronischen Mautdienstes und seiner technischen Komponenten (EEMD)

Dem Prüflaboratorium ist, ohne dass es einer vorherigen Information und Zustimmung der DAkkS bedarf, die Anwendung der hier aufgeführten genormten oder ihnen gleichzusetzenden Prüfverfahren mit unterschiedlichen Ausgabeständen gestattet.
Das Prüflaboratorium verfügt über eine aktuelle Liste aller Prüfverfahren im flexiblen Akkreditierungsbereich.

verwendete Abkürzungen: siehe letzte Seite

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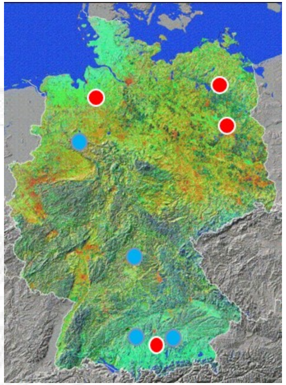
DLR EOC Profile

DLR – Earth Observation Center (EOC)

- Remote Sensing Technology Institute (IMF)
- German Remote Sensing Data Center (DFD)

→ @ German Aerospace Center (DLR)

7 sites in Germany
Headquarter in Oberpfaffenhofen close to Munich



Staff: 250/150 (DFD/IMF)

DLR EOC Profile

DLR – Remote Sensing Technologies @ EOC

Synthetic Aperture Radar (SAR)

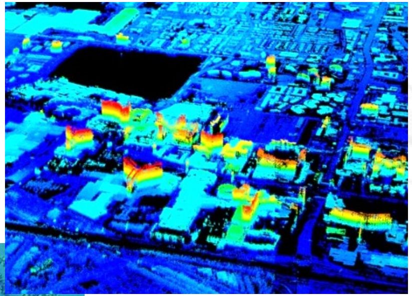
- Processors for Sentinel-1, TerraSAR-X, TanDEM-X, PAZ, Tandem-L, etc.
- Imaging geodesy
- 4D imaging: PSI, SAR tomography et al.
- SAR oceanography, maritime security

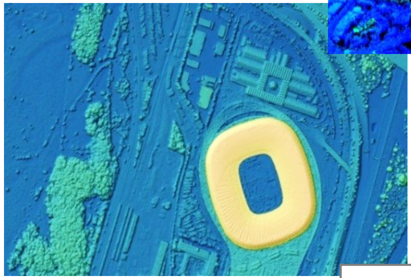
Optical Imaging

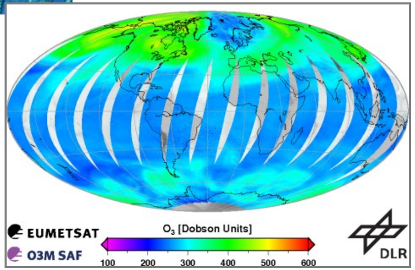
- Processors for Sentinel-2, EnMAP and DESIS
- CATENA: generic processing chain for satellite and airborne sensors
- 3D: dense stereo matching and object reconstruction, computer vision
- Hyperspectral methods: retrieval, unmixing, classification, fusion
- Atmospheric correction, ocean color, water quality
- Airborne applications/Traffic monitoring

Atmospheric Spectrometry and Lidar

- Processors for GOME-2, ADM, MERLIN, Sentinel 5p/4/5, etc.
- Spectrometry laboratory
- Scattering theory, radiative transfer, inversion methods







VaGAD Context

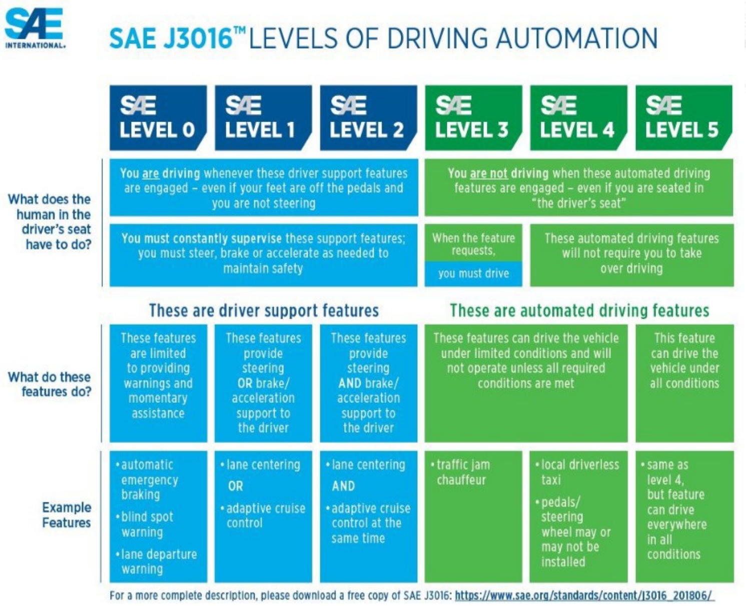
- The high-precision determination of absolute vehicle positions required for autonomous driving is a new and a considerable challenge for the automotive industry.
- Positioning functions in the automotive sector have been used for applications where positioning accuracy is not so stringent.
- Positioning functions have only been used as a commodity of convenience for basic functions such as navigation or for the provision of points of interest (PoI's).
- However, for vehicles with automated driving functions, specifically designed to reach the SAE-L3, and SAE-L4 position accuracy is critical.

VaGAD Context

- Human driver will be substituted incrementally with increasing levels of automation
  → for SAE-L3, SAE-L4 and higher the position accuracy is a critical element

- The **VaGAD project** emerged from the need to address calibration, validation, and certification of GNSS receivers supporting SAE-L3, and SAE-L4 functions.

- The focus of the project lies on the calibration, validation and certification of the absolute positional accuracy



VaGAD Context

- Prove of evidence regarding the vehicle's required position accuracy is important for the functionality of the automated driving systems.
- The vehicle's **absolute** position can only be determined by using GNSS devices supported optionally by auxiliary sensors, e.g. INS, odometer.
- The prove of evidence regarding accuracy is done by using the same GNSS technology using a high-grade device.
- Tier's require an independent method for validation during development and production.
- OEMs are looking for an independent method to verify their GNSS specific Key Performance Indicators (KPIs) in the delivered products.

VaGAD Context

- An independent method for testing is important for certification
  - The accuracy assessment of GNSS devices uses the same working and test principles as the device under test, i.e. by using a high-grade GNSS receiver with an assumed higher accuracy and performance.
  - This approach tends to ignore the fact that by using the same working principles the reference as well as the test devices will suffer of the same underlying error problems.
- The real or intrinsic accuracy of GNSS receivers is unknown or quite difficult to estimate.
- An independent procedure to assess the accuracy of GNSS devices is highly desirable and necessary, particularly in GNSS-denied areas and in safety applications as in AD
- Certification is a quality stamp which assures that a product fulfils at least a minimum set of requirements from standard(s) or industry agreed requirements.

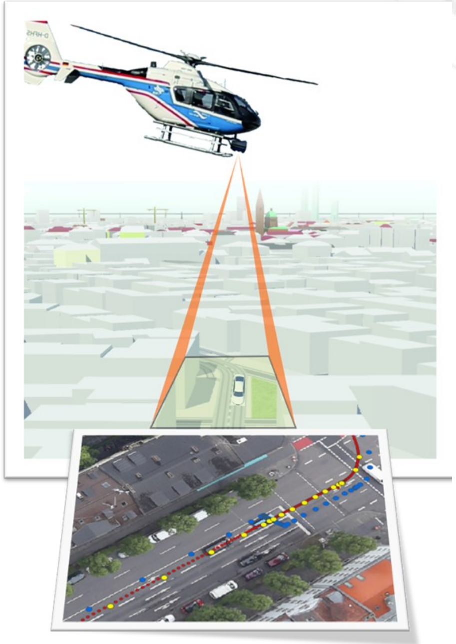
Certification & Validation

- **Product certification**
  - rises awareness,
  - establishes consensus among manufactures, providers, users, and regulators,
  - develops trust on the product,
  - defines a state-of-art product.
- The **VaGAD calibration and validation service** is based on the comparison of measurement values delivered by a GNSS receiver with those obtained by a validated GNSS independent system.
- The **VaGAD calibration and validation service** allows the calibration and the validation of GNSS receivers for the automotive industry under real world conditions through the use of aerial images and GCP's data (e.g., satellites).

Certification & Validation

The VaGAD calibration and validation service provides

- a GNSS independent reference system and a reference trajectory **without** the same underlying errors as the device under test,
- a GNSS independent reference trajectory used in critical areas, e.g. urban canyons or other GNSS-denied environments,
- a new method for calibration, validation and certification of GNSS-based positioning systems and for classification in performance classes,
- three categories of accuracy levels, i.e., highway, urban or rural,
- and a valid **test scheme** with a **test plan** comprising
  - test method based on specifications or standards
  - including decision rules for pass-fail classification.



Certification & Validation

VaGAD Test Case requirements

Test Track Requirements

R01	Availability of sufficient [1)] ground control and check points with high accuracy (derived from SAR satellite data or measured locally with GNSS receivers)
R02	Availability of high-resolution LiDAR surface models of the road surface
R03	Flight clearance for helicopter and flight corridors outside of airport control area, if possible
R04	Visibility of test vehicle from the helicopter (except for tunnels and under bridges)
R05	Challenging test area for mobile GNSS receivers installed in the vehicles, i.e. multipath-effects and effects due to poor reception
R06	Coverage of different scenarios like urban roads (within the city surrounded by buildings), rural roads (outside the city centre with few buildings) and motorways
R07	Avoidance of noise pollution for residents
R08	Measurements number according to test scenario (urban=625 [2)] @1Hz, rural=400 [2)] @1Hz and highway=230 [2)] @1Hz)
R09	Avoidance of traffic jams [3)]
R10	Availability LTE network coverage for use of the vehicle tracking tool in the helicopter
R11	Free waiting zones for the measuring vehicle, if synchronisation with helicopter is needed

Rural scenario

Urban scenario

Three scenarios: Rural, Highway and Urban, and in addition a calibration track

Certification & Validation

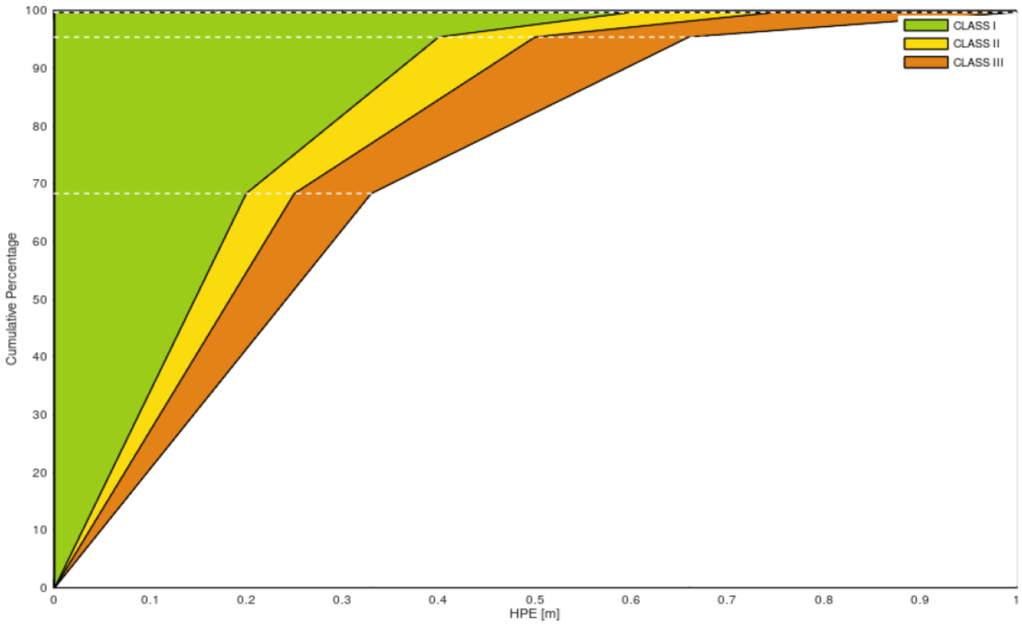
Defined Test Cases in the VaGAD project

Test Track	Reference (Control)	Track 1A	Track 2A	Track 2B	Track 3A	Track 3B	Track 3C	Track 3D	Track 3E
Type	Rural	Rural	Highway	Highway	Urban	Urban	Urban	Urban	Urban
Start LAT: LON:	N 47.997601 E 11.641396	N 47.995260 E 11.650159	N 48.030568 E 11.634930	N 48.056165 E 11.598043	N 48.094797 E 11.588305	N 48.118735 E 11.558475	N 48.1358913 E 11.5513249	N 48.1402914 E 11.5241176	N 48.1426814 E 11.5678418
End LAT: LON:	N 47.996135 E 11.655278	N 48.030539 E 11.634944	N 48.056173 E 11.597982	N 48.094805 E 11.588295	N 48.118041 E 11.558847	N 48.135855 E 11.551282	N 48.1402970 E 11.5241099	N 48.1473704 E 11.5518234	N 48.1473737 E 11.5518265
Length	1 km	4.5 km	5.3 km	4.6 km	4.7 km	2.4 km	2.4 km	2.8 km	1.5 km
Sky view	Open sky	Limited sky	Open sky (mostly)	Open sky	Limited sky .	Limited sky	Limited sky	Limited sky	Limited sky
Physical Environment	Fields	Forest	Forest (distant) and fields	Fields (mostly).	Buildings, trench, small crossovers.	Buildings (height ~30 m)	Buildings (height ~20 m)	Buildings (height ~20 m)	Buildings (height ~20 m)
Elevation Mask (min)	> 5°	~40° – 70°	> 10° – 20°	> 5° – 10°	~30° – 80°	~30° – 60°	~30° – 60°	~30° – 60°	~30° – 60°
Factors Impacting the GNSS signals in the test track	-/-	High absorption, middle blockage effects	Weak absorption, weak blockage effects	Weak multipath effects	Strong multipath, blockage, and diffraction effects	Middle multipath, blockage, and diffraction effects	Middle multipath, blockage, and diffraction effects	Middle multipath, blockage, and diffraction effects	Middle multipath, blockage, and diffraction effects
Standard Reference[2](s)	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3	CEN/EN 16803-1 ETSI 103 246-3
Velocity range	0 – 30 km/h	40 – 80 km/h	80 – 100 km/h	80 – 120 km/h	30 – 60 km/h	30 – 60 km/h	30 – 60 km/h	30 – 60 km/h	30 – 60 km/h
-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-

Test tracks/test case definition, physical and environmental characteristics

Certification & Validation

Defined accuracy class levels and a certification mark



This follows the classification principles from the CEN/CENELEC and ETSI ESO's.

Certification & Validation

Defined accuracy class levels and Pass/Fail Criteria

Accuracy Class Levels

Accuracy Metrics	**Position Error**		
	Class I: Urban	Class II Rural	Class III Highway
	Maximum Horizontal Position Error [m]		
HPE | 68.3^{th} percentile	$\leq$ 0.20	$\leq$ 0.25	$\leq$ 0.33
HPE | 95.4^{th} percentile	$\leq$ 0.40	$\leq$ 0.50	$\leq$ 0.66
HPE | 99.7^{th} percentile	$\leq$ 0.60	$\leq$ 0.75	$\leq$ 1.00
	Maximum Vertical Position Error [m]		
VPE | 68.3^{th} percentile	$\leq$ 1.00	$\leq$ 1.20	$\leq$ 1.50
VPE | 95.4^{th} percentile	$\leq$ 2.00	$\leq$ 2.40	$\leq$ 3.00
VPE | 99.7^{th} percentile	$\leq$ 3.00	$\leq$ 3.60	$\leq$ 4.50

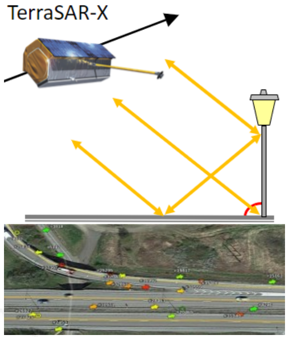
Certification Mark

The 95.4^{th} percentile is also used to defined **Pass/Fail criteria** in the context of a certification process.

VaGAD Method

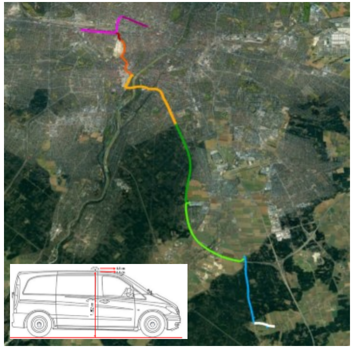
VaGAD working principle

Aerial Imagery



Ground Control Points

Digital Surface Model



Vehicle GNSS Data

VaGAD Method

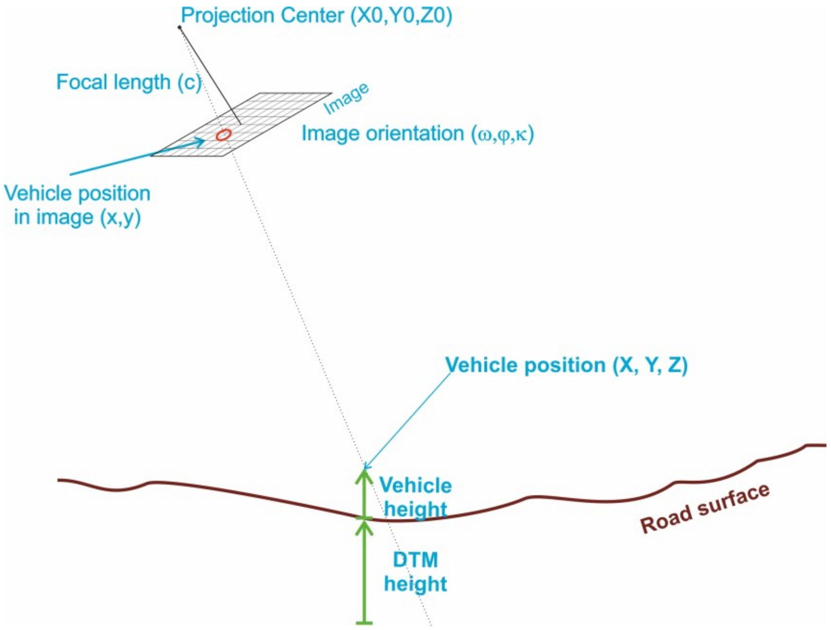
VaGAD working principle

- Aerial imagery can be used to determine exact positions of moving objects.
- Aerial images are acquired simultaneously above the reference vehicle from a flying platform.
- „Forward ray intersection“ provides the vehicle position.
- Image 2D to real world 3D $\rightarrow$ height required.
- Height information gets derived from an external data source.

Collinearity equation

$$x = -c\,\frac{r_{11}(X-X_0)+r_{12}(Y-Y_0)+r_{13}(Z-Z_0)}{r_{13}(X-X_0)+r_{23}(Y-Y_0)+r_{33}(Z-Z_0)}$$

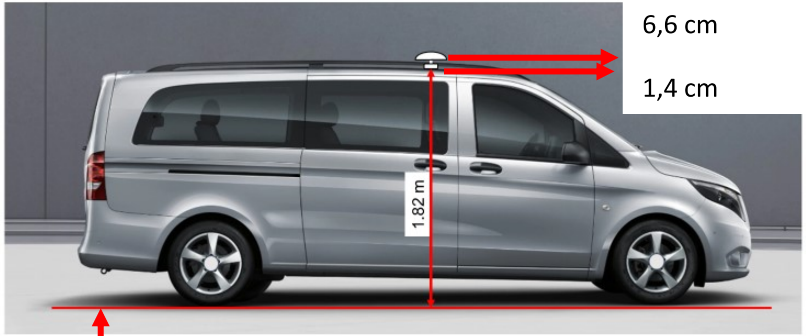
$$y = -c\,\frac{r_{12}(X-X_0)+r_{22}(Y-Y_0)+r_{23}(Z-Z_0)}{r_{13}(X-X_0)+r_{23}(Y-Y_0)+r_{33}(Z-Z_0)}$$



VaGAD Method

VaGAD working principle – Height information

Total height = 182.0 + 1.4 + 6.6 = 190 cm



6,6 cm

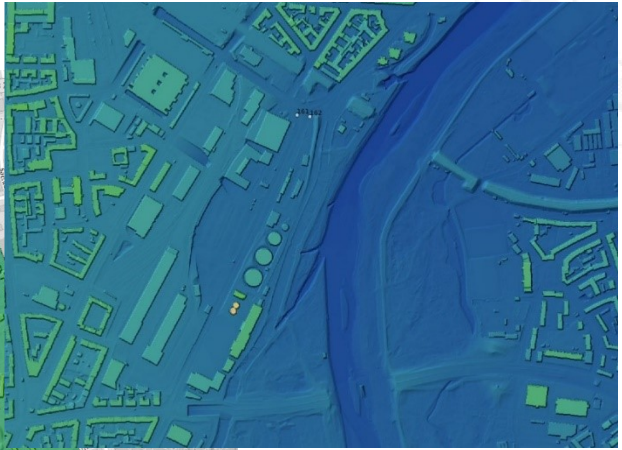
1,4 cm

LIDAR Digital Terrain Model

LIDAR Digital Terrain Model + LOD1
(red: errors at briges)

VaGAD working principle – Height information

- LIDAR DTM from state of Bavaria + LOD1 building model
  - ETRS89/DREF91, DHNN2016
- 4 pts/m^2
- <10cm accuracy in Z
- Errors at bridges (areas must be excluded from processing)



VaGAD Method

Data preparation – Ground control and check points

- Stationary GNSS measurements
  - 26 GCPs
  - 17 ChPts
  - Σ43 Pts.
- Difference to LIDAR DTM < 5cm (!)

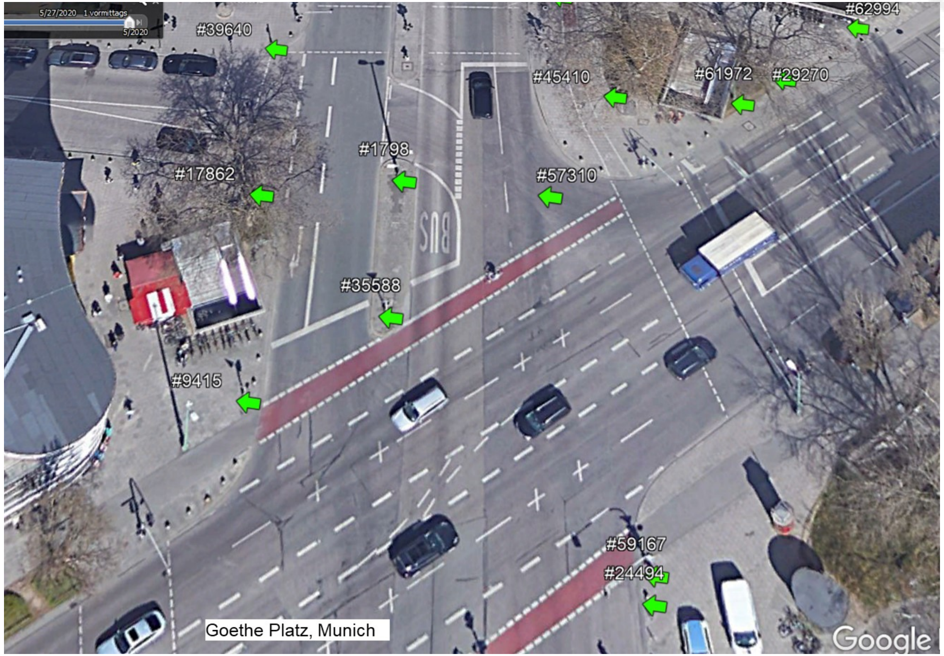
- Processing of SAR geodetic points from TerraSAR-X satellite data as optional ground control points

Nr	UTM_X	UTM_Y	UTM_Z	DTM	dH	remark	SIGMA_X	SIGMA_Y	SIGMA_Z
62	698032,52	5319276,11	644,67	644,69	0,02		0,0103	0,0042	0,0094
61	698056,56	5319282,14	644,74	644,71	-0,03		0,0091	0,0043	0,0080
60	698062,60	5319284,01	644,64	644,6	0,02	Road surface	0,0088	0,0041	0,0077
63	697669,26	5319334,86	643,67	643,72	0,05	#nr sat.<15	0,0120	0,0058	0,0105
71	697181,76	5319412,74	645,10	645,1	0,01	Road surface	0,0100	0,0057	0,0082
52	696903,95	5319954,04	641,85	641,85	0,00	Road surface	0,0142	0,0095	0,0107
51	696689,07	5320777,18	636,14	636,00	-0,14	#nr sat.<15	0,0075	0,0044	0,0061
...	...	...							

VaGAD Method

Ground Control Points From TerraSAR-X Geodetic Measurements

- TerraSAR-X Staring Spotlight Mode
- Several hundred GCPs with an accuracy of 4-6 cm in X,Y and Z have been generated for the region around the test track
- The techniques allows the determination of the geodetic coordinates of the foot point of poles (and other corner reflectors)
- Poles can be recognized in airborne images by their black shadow line



Ground Control Points From TerraSAR-X Geodetic Measurements

- Unfortunately, the VaGAD helicopter flights had to be performed on cloudy days with no shadows.
- As a result, the masts were practically invisible in the aerial images and the coordinates of the base points could not be assigned.
- GCPs obtained with traditional methods had to be used.

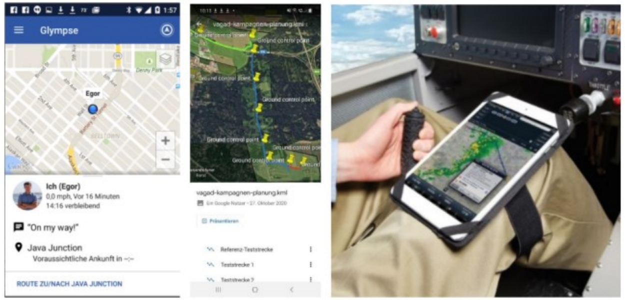
parameter	value	unit
reference frame	ETRF2000	
earth ellipsoid	WGS84	
latitude	48.129777054	deg N
longitude	11.558359396	deg E
ellipsoid height	567.0825	m
cartesian coordinate X	4178864.9816	m
cartesian coordinate Y	854633.2357	m
cartesian coordinate Z	4726942.0923	m
epoch	2020.115	
date	2020-02-12	
localization accuracy (range)	3.21	cm
localization accuracy (azimuth)	1.81	cm
localization accuracy (elevation)	4.23	cm
localization accuracy (X)	4.79	cm
localization accuracy (Y)	4.80	cm
localization accuracy (Z)	5.12	cm
localization accuracy (north)	2.41	cm
localization accuracy (east)	5.21	cm
localization accuracy (height)	5.31	cm
unit vector (range)	(0.2735, 0.8973, 0.3464)	
unit vector (azimuth)	(0.7474, 0.0272, -0.6638)	
unit vector (elevation)	(-0.6051, 0.4405, -0.6632)	

VaGAD Test Campaign

Equipment and test architecture – 4k Camera System on EC135

4k camera system on EC135:
Two cameras
- 35mm
- 50mm focal length

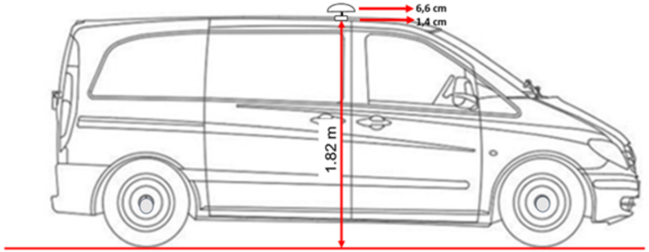
1 fps, GSD (10cm resp. 7cm @ 500m)

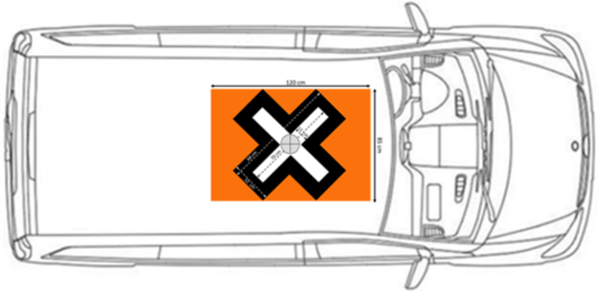


Vehicle tracking hard- and software for helicopter pilots

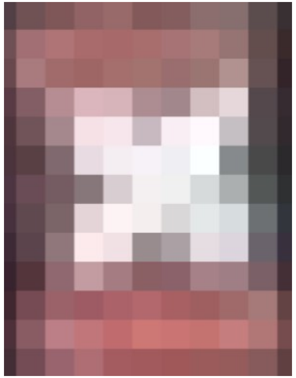
VaGAD Test Campaign

Equipment and test architecture – reference vehicle



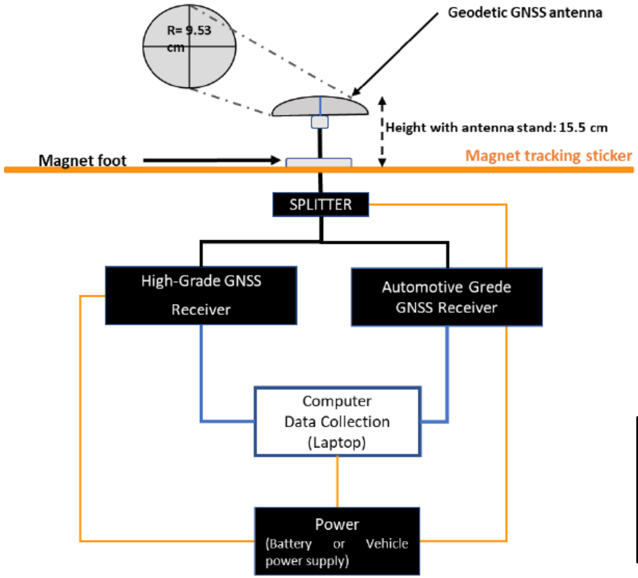



Original


10cm GSD


7cm GSD

Equipment and test architecture - GNSS equipment in reference vehicle



High-grade Receiver
GPS, GLONASS, BeiDou, Galileo

Multipath mitigation, interference mitigation, ionospheric correction

DGPS (only for CALIB):
SAPOS GPPS, GPS/GLONASS
0.02m/0.03m, 10Hz

DGPS (only 14/07/2021):
SAPOS EPS (RTK), 10Hz, 0.8m

DGPS (only 15/07/2021):
SBAS (EGNOS) for GPS, 10Hz

Output
RINEX Format,
ETRS89/DREF91, DHNN2016

Output
NMEA Format,
WGS84, Geoid heights
Transformation ITRF/ETRF

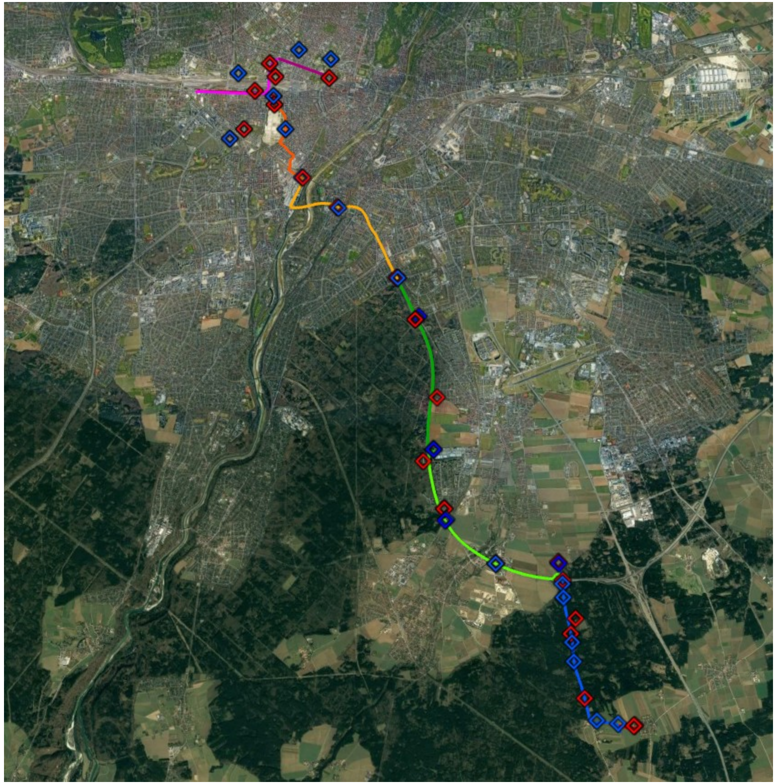
Automotive Type Receiver
GPS, GLONASS, Galileo

DGPS:
SBAS (EGNOS) for GPS
1.5 m horizontal, 1Hz

Output
NMEA Format,
WGS84, Geoid heights
Transformation ITRF/ETRF

VaGAD Test Campaign

Test Site



Yellow/Orange/Red/Pink: Urban scenario

Green: Highway scenario

Blue: Rural scenario / Calibration track

Blue symbols: Check points

Red symbols: Ground control points

VaGAD Test Campaign

Test Campaign

The test campaign was performed on the 13th, 14th and 15th of July 2021.

Analysis and results will be based only on data from 14th and 15th July

Two receivers were used, one with the capability to use RTK corrections (used on the 14th).

Number of aerial images

	Camera 35mm # **/total images	Camera 50mm # **/total images
13.07.2021	-------/5441	-------/5441
14.07.2021	3705/4331	3130/4331
15.07.2021	3123/3767	2529/3767

**R04/R08/R09 fulfilled

Test Campaign

Data completeness for each scenario and compliance to sample size

		Camera 35mm # **/total images	Camera 50mm # **/total images	R04/R08/R09 #required images
14.07.2021	CAL	0438/0500	0401/0500	-
With RTK	RURAL	0676/0817	0486/0817	400
	HIGHWAY	1476/1716	1294/1716	230
	URBAN	1115/1298	0949/1298	625
15.07.2021	CAL	0388/0500	0326/0500	-
Without RTK	RURAL	0642/0666	0601/0666	400
	HIGHWAY	0710/1032	0543/1032	230
	URBAN	1383/1569	1059/1569	625

VaGAD Test Campaign

Test Campaign

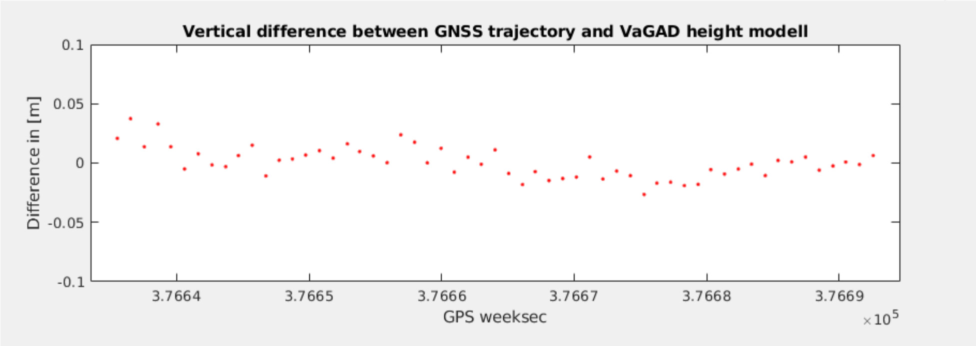
Visualisation of data completeness for each scenario on the 15th of July

RURAL HIGHWAY HIGHWAY URBAN

Analysis & Results

Verification of DTM+vehicle heights

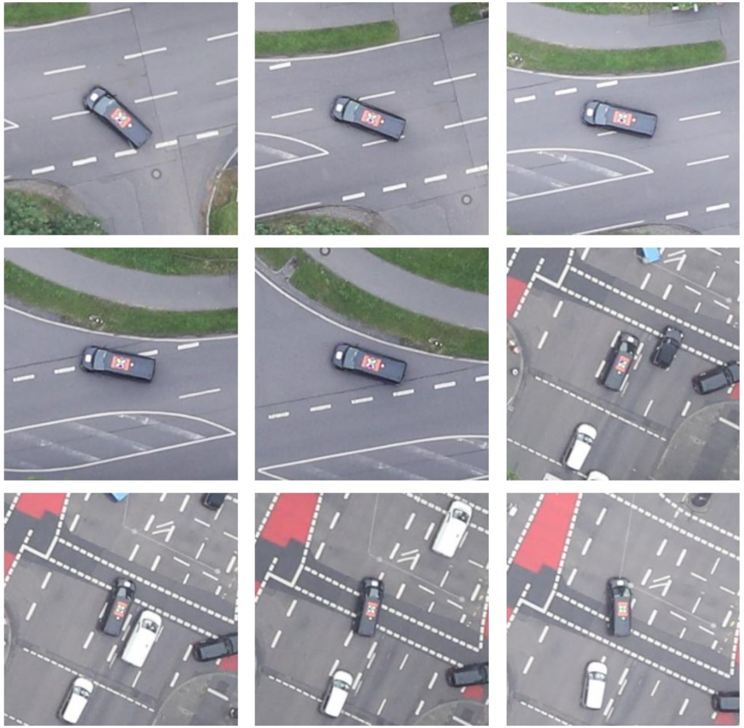
- Analysis at Calibration track
- Differences between GNSS positions (post-processed) and DTM+vehicle heights are far better than specified
- No additional corrections of the DTM are required



		Mean (#57 images)	Std (#57 images)
15.07.2021	CAL	0.1 cm	1.2 cm

VaGAD pattern position tracking in image sequences

- Pattern matching using NCC (normalized cross correlation)
- Search space limited by using approximated position
- Search for -180°/180°angle range
- Performance:
    - >95% of all positions are correct (altogether ~5000 positions)
    - Problems at occlusions and with wrong approximation
    - Manual check required



Analysis & Results

VaGAD Bundle adjustment of image sequences

VaGAD flight configuration not ideal for highly accurate position accuracies

- Helicopter stops, changes speed
- Mostly no parallel flight strips

All images from 14/07/21 and 15/07/21 were adjusted in six image blocks

4k aerial sensor latency** was estimated separately: 0.003 s

	Tie points			Ground control			Image position and attitude					
Track	#images	#tie pts	#tie coords	#GPSIMU	#gcps	#coords	#chkpts	RMS_{ω}	RMS_{φ}	RMS_{κ}	RMS_{X0}	RMS_{Y0}	RMS_{Z0}
CALIB	690	19746	2.18e06	4416	3	138	2	0.004°	0.004°	0.005°	0.02m	0.02m	0.01m
RURAL	1412	39530	2.45e06	8472	7	197	4	0.004°	0.004°	0.005°	0.02m	0.02m	0.02m
$HIGH_{14/07/21}$	964	72439	2.20e06	5784	9	87	6	0.004°	0.004°	0.005°	0.03m	0.03m	0.02m
$HIGH_{15/07/21}$	485	34158	0.58e06	2910	7	82	6	0.005°	0.005°	0.007°	0.03m	0.04m	0.02m
$URBAN_{14/07/21}$	2376*	96356	2.30e06	14256	11	122	4	0.004°	0.004°	0.005°	0.03m	0.03m	0.01m
$URBAN_{15/07/21}$	2589*	69866	1.90e06	15534	11	134	4	0.004°	0.004°	0.006°	0.03m	0.03m	0.01m

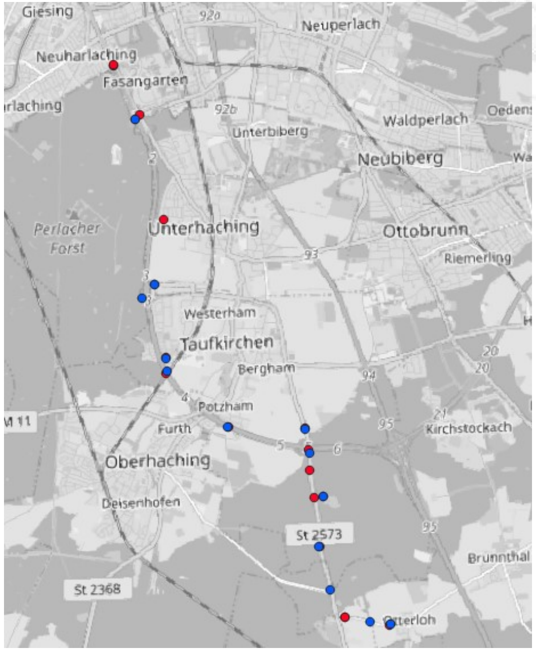
**Sensor latency: time stamp of aerial image – real time of acquisition

* With additional images

VaGAD Positional accuracy of image sequences: Rural/Motorway

- Images georeferenced with 19 GCP (only GNSS)
- Accuracy checked with 11 check points (only GNSS)
- RMSX 0.064 m RMSY 0.056 m RMSZ 0.109 m

Nr	X	Y	Z	dX	dY	dZ
61	698056.570	5319282.144	644.720	0.010	0.004	-0.020
63	697669.322	5319334.984	643.479	0.062	0.128	-0.191
21	696491.259	5322581.868	628.103	-0.033	0.035	-0.077
81	696419.975	5323056.976	619.791	-0.009	-0.042	0.041
31	696769.333	5321759.353	627.779	0.060	-0.037	-0.001
52	696903.901	5319953.954	641.731	-0.045	-0.090	-0.119
12	694919.594	5323092.833	624.708	-0.028	-0.017	0.078
93	693758.273	5324159.548	622.028	0.064	-0.013	-0.022
101	693730.669	5324412.951	620.424	0.107	-0.007	0.134
112	693504.346	5325845.676	608.156	-0.037	0.029	0.156
132	693142.579	5329020.281	601.187	0.006	-0.054	0.177



Blue: chkpt Red: gcp

Analysis & Results

VaGAD Positional accuracy of image sequences: Urban

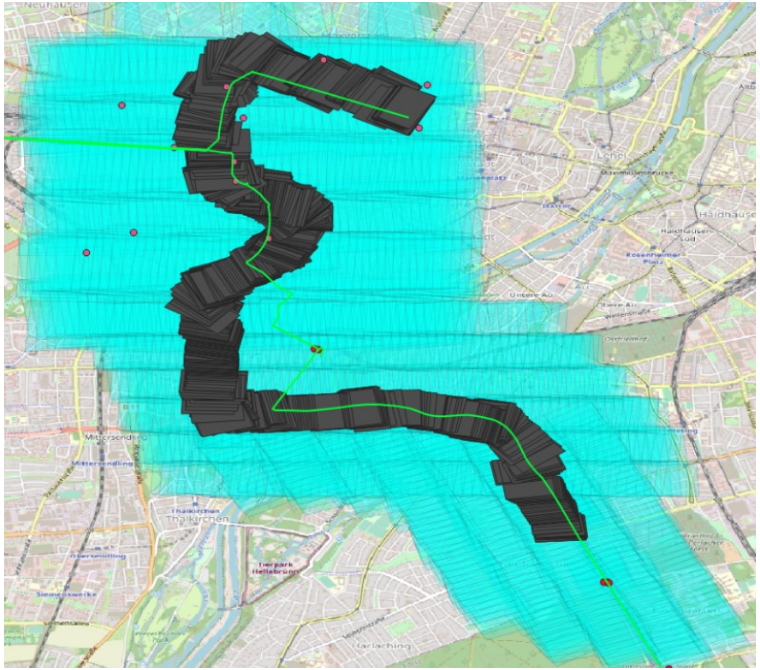
- Images georeferenced with 7 GCP (only GNSS)
- Accuracy checked with 4 check points (only GNSS)
- RMSX 0.075 m RMSY 0.069 m RMSZ 0.096 m

Nr	X	Y	Z	dX	dY	dZ
161	690385.374	5332672.123	565.262	0.011m	0.019m	0.072m
10018	689992.667	5333927.174	567.728	-0.058m	0.061m	-0.125m
10010	689234.283	5334942.164	570.577	0.110m	0.099m	-0.075m
10021	689697.537	5334792.340	565.704	0.084m	0.073m	-0.103m
RMS				0.075m	0.069m	0.096m

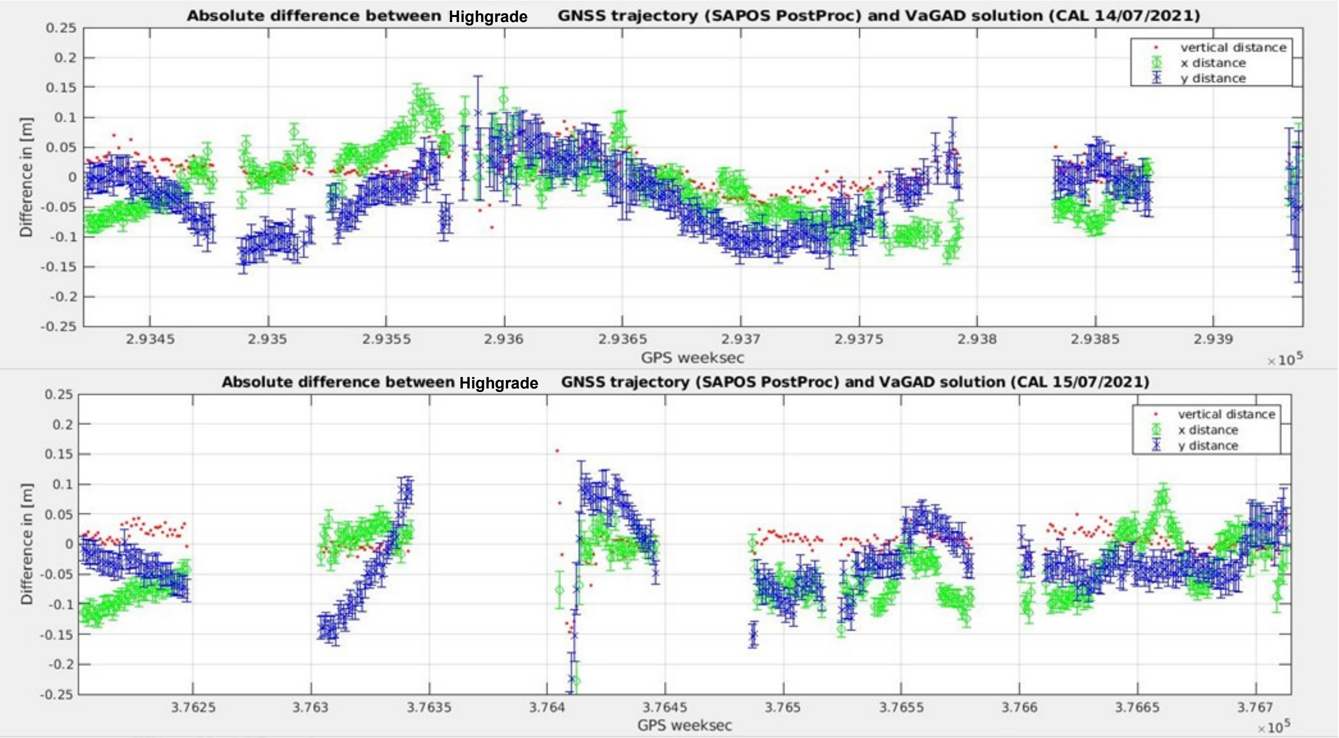
Analysis&Result

VaGAD Positional accuracy of image sequences: Urban

- Track changed short-term due to construction zones in the city
- GNSS control points were not covered by the image sequences
- To avoid additional GNSS measurements, aerial images from a regular strip configuration (cyan footprints) were added to the image sequences (black footprints)
- All control points were then covered



VaGAD Results – Calibration tracks



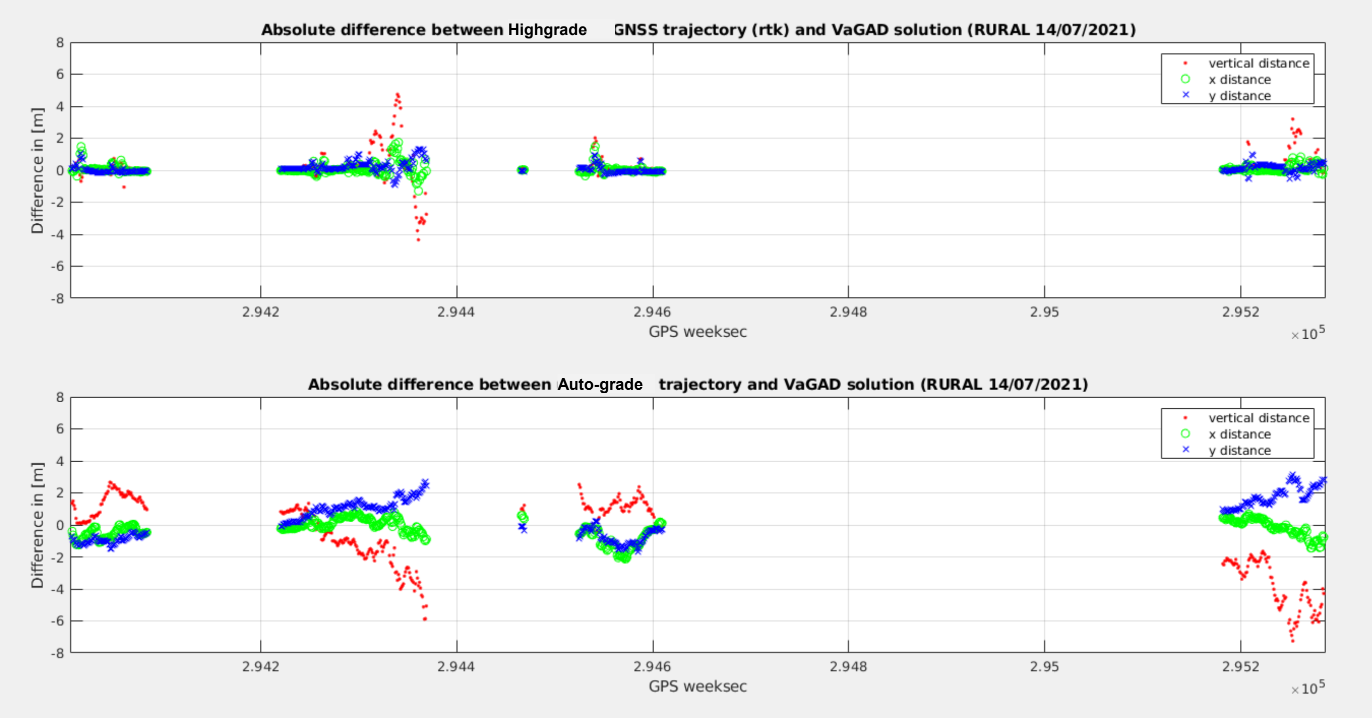
Analysis & Results

VaGAD Results – Calibration tracks

Device/Track	Date	$\#pts$	RMS_X	RMS_Y	$p_{DIST}^{68.3\%}$	$p_{DIST}^{95.4\%}$	$p_{DIST}^{99.7\%}$
High-grade	14.07.2021	360	0.06	0.06	0.09	0.12	0.15
High-grade	15.07.2021	302	0.06	0.06	0.09	0.13	0.17

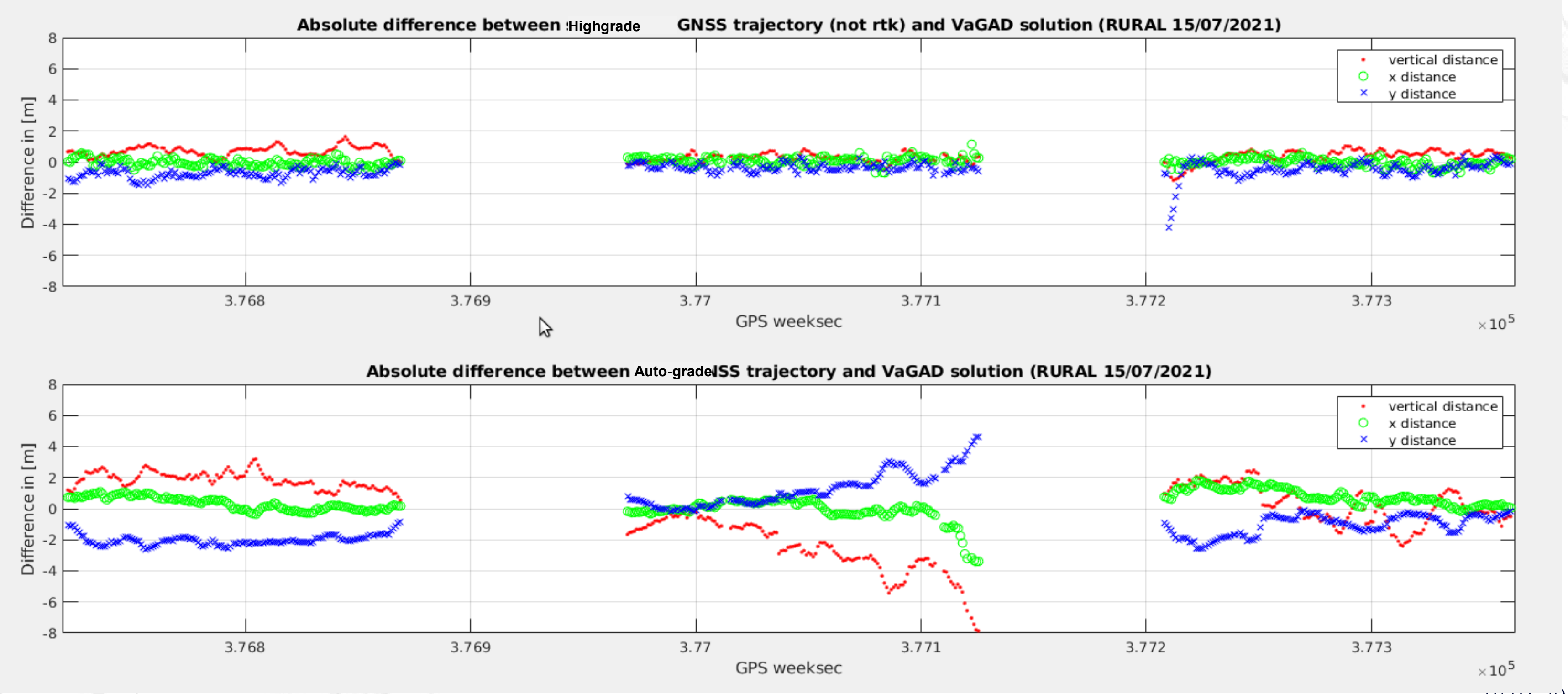
In meter

VaGAD Results – Rural tracks



Analysis & Results

VaGAD Results – Rural tracks



Analysis & Results

Test Campaign on the 14th of July 2021

- Automotive type receiver versus high-grade-RTK receiver

- VaGAD Solution
- Automotive Type
- High-grade-RTK Type

Test Campaign on the 14th of July 2021

- **Automotive type receiver versus high-grade-RTK receiver**

- VaGAD Solution
- High-grade-RTK Type

Analysis & Results

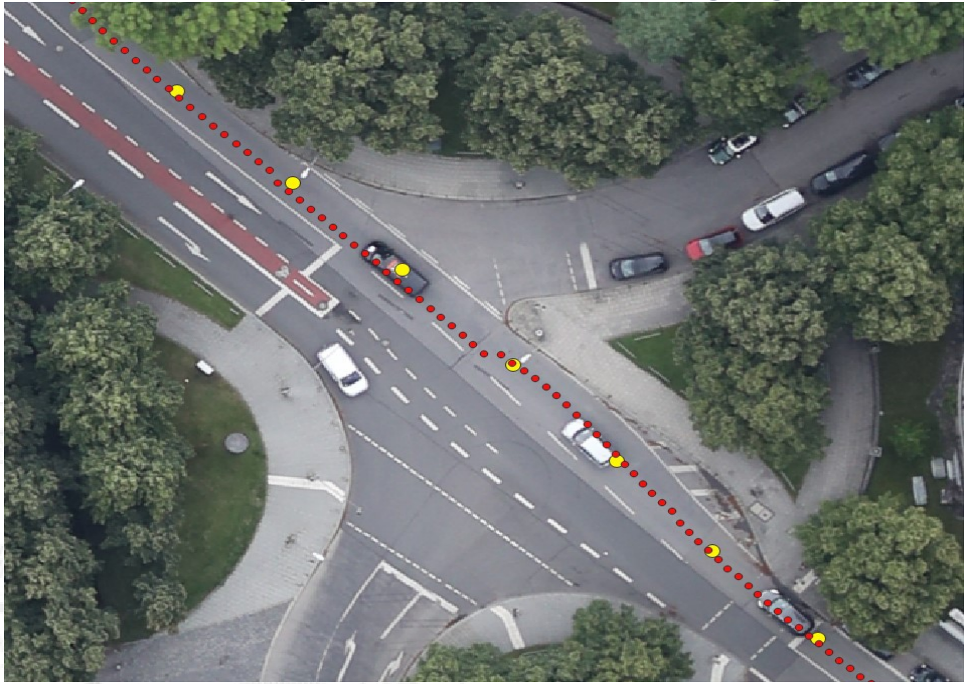
Test Campaign on the 14th of July 2021

- **Automotive type receiver versus high-grade-RTK receiver**

- VaGAD Solution
- High-grade-RTK Type

Test Campaign on the 14th of July 2021

- Automotive type receiver versus high-grade-RTK receiver



- VaGAD Solution
- High-grade-RTK Type

Analysis & Results

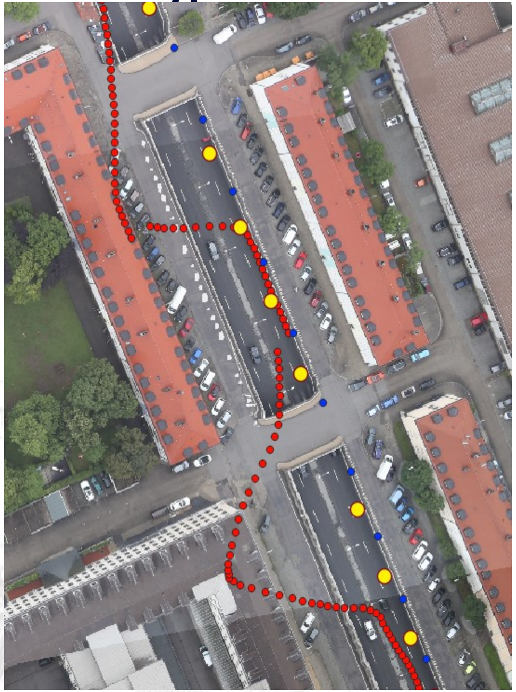
Test Campaign on the 14th of July 2021

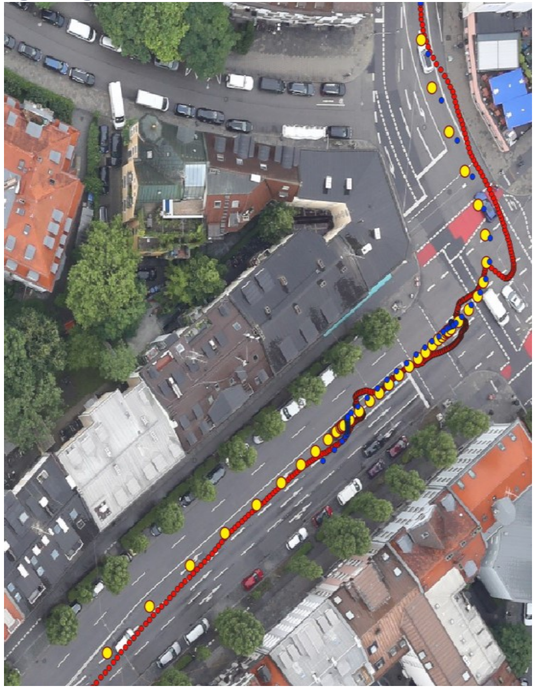
- **Automotive type receiver versus high-grade-RTK receiver**

- VaGAD Solution
- High-grade-RTK Type

Test Campaign on the 15th of July 2021

- **Automotive type receiver versus high-grade receiver without RTK**



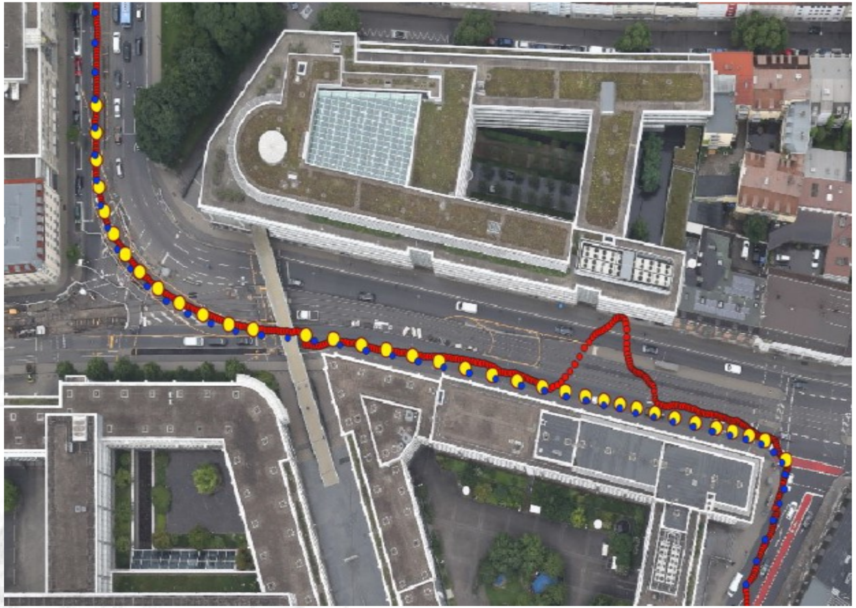


- VaGAD Solution
- Automotive Type
- High-grade Type

Analysis & Results

Test Campaign on the 15th of July 2021

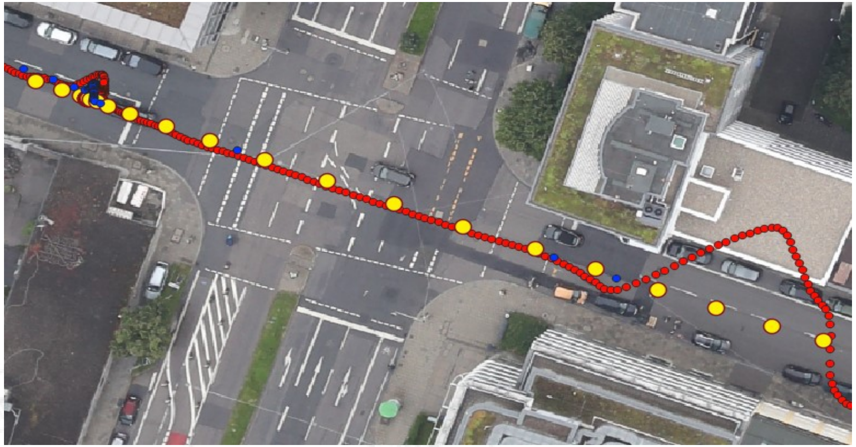
- **Automotive type receiver versus high-grade receiver without RTK**



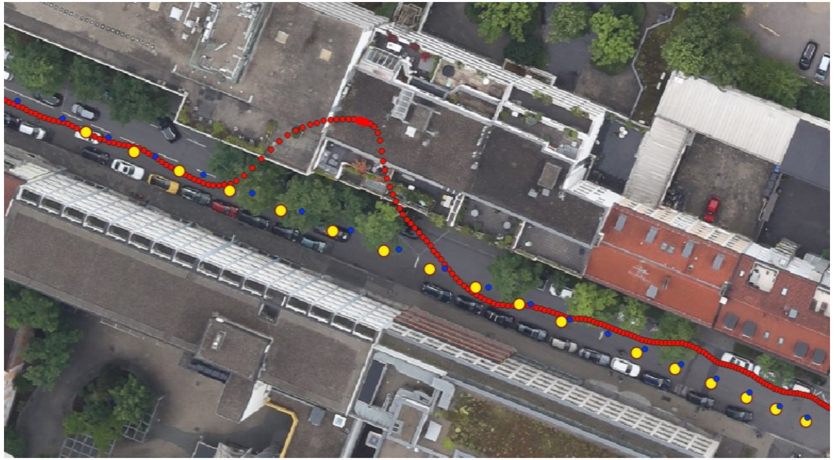
- VaGAD Solution
- Automotive Type
- High-grade Type

Test Campaign on the 15th of July 2021

- **Automotive type receiver versus high-grade receiver without RTK**



- VaGAD Solution
- Automotive Type
- High-grade Type



  18.01.2022

Analysis & Results

Track Case/Device	Test Date	Measurement samples used	RMS_X [m]	RMS_Y [m]	μ_{HPE} [m]	σ_{HPE} [m]	μ_{VPE} [m]	σ_{VPE}[m]
Rural								
High-Grade	14.07.2021	408	0.34	0.34	0.33	0.35	0.28	0.98
High-Grade	15.07.2021	442	0.25	0.67	0.60	0.39	0.45	0.39
Automotive-Grade	14.07.2021	408	0.69	1.31	1.31	0.69	-0.92	2.35
Automotive-Grade	15.07.2021	442	0.78	1.67	1.61	0.90	-0.14	2.20
Highway								
High-Grade	14.07.2021	637	0.11	0.17	$\boxed{0.18}$	0.09	$\boxed{0.06}$	0.05
High-Grade	15.07.2021	437	0.21	0.30	0.34	0.16	0.03	0.24
Automotive-Grade	14.07.2021	637	0.29	0.44	0.47	0.25	-0.41	1.37
Automotive-Grade	15.07.2021	437	0.76	0.87	0.98	0.61	-2.21	0.88
Urban								
High-Grade	14.07.2021	736	0.35	0.45	0.34	0.46	0.12	1.34
High-Grade	15.07.2021	912	2.07	2.28	1.61	2.87	1.61	2.62
Automotive-Grade	14.07.2021	733	0.76	1.09	1.09	0.76	-0.38	2.06
Automotive-Grade	15.07.2021	912	0.55	1.13	1.04	0.73	-2.04	2.62

Analysis & Results

Track Case/Device	Test Date	Measurement samples used	$p_{HPE}^{68.3th}$ [m]	$p_{HPE}^{95.4th}$[m]	$p_{HPE}^{99.7th}$[m]	$p_{VPE}^{68.3th}$[m]	$p_{VPE}^{95.4th}$[m]	$p_{VPE}^{99.7th}$[m]
Rural								
High-Grade	14.07.2021	408	0.33	1.24	1.81	0.25	2.76	4.60
High-Grade	15.07.2021	442	0.30	1.20	3.71	0.68	1.06	1.45
Automotive-Grade	14.07.2021	408	1.56	2.75	3.07	2.22	5.65	6.90
Automotive-Grade	15.07.2021	442	2.12	2.90	5.73	2.08	4.71	7.79
Highway								
High-Grade	14.07.2021	637	0.21	$\boxed{0.34}$	0.62	0.07	$\boxed{0.11}$	0.37
High-Grade	15.07.2021	437	0.41	0.60	1.05	0.24	0.47	0.83
Automotive-Grade	14.07.2021	637	0.60	0.90	1.09	1.27	2.97	3.32
Automotive-Grade	15.07.2021	437	1.25	1.79	3.96	2.63	3.94	4.45
Urban								
High-Grade	14.07.2021	736	0.29	0.86	4.74	0.06	1.26	16.75
High-Grade	15.07.2021	912	1.51	4.33	26.46	1.90	5.90	20.07
Automotive-Grade	14.07.2021	733	1.18	2.23	3.48	2.30	4.01	6.39
Automotive-Grade	15.07.2021	912	1.21	2.48	5.82	3.90	5.75	6.41

Analysis & Results

Test Case 1: Highway Recertification: N/A		
Horizontal Position Error (HPE) ≤ 0.66 m The 95.4th percentile of the cumulative distribution of the HPE ≤ 0.66 m	P F	0.47 m 0.90 m
Vertical Position Error (VPE) ≤ 3.0 m The 95.4th percentile of the cumulative distribution of the VPE ≤ 3.0 m Class III	P P F	-0.41 m 2.97 m -/-
Accuracy Analysis		
Test Case 2: Rural Recertification: N/A		
Horizontal Position Error (HPE) ≤ 0.50 m The 95.4th percentile of the cumulative distribution of the HPE ≤ 0.50 m	F F	1.31 m 2.75 m
Vertical Position Error (VPE) ≤ 2.4 m The 95.4th percentile of the cumulative distribution of the VPE ≤ 2.4 m Class II	P F F	-0.92 m 5.65 m -/-
Accuracy Analysis		
Test Case 3: Urban Recertification: N/A		
Horizontal Position Error (HPE) ≤ 0.40 m The 95.4th percentile of the cumulative distribution of the HPE ≤ 0.40 m	F F	1.10 m 2.23 m
Vertical Position Error (VPE) ≤ 2.0 m The 95.4th percentile of the cumulative distribution of the VPE ≤ 2.0 m Class I	P F F	-0.38 m 4.01 m -/-

Automotive Type Receiver

No Certification Mark Possible!

Analysis & Results

Test Case 1: Highway Recertification: N/A		
Horizontal Position Error (HPE) ≤ 0.66 m	P	0.18 m
The 95.4th percentile of the cumulative distribution of the HPE ≤ 0.66 m	P	0.34 m
Vertical Position Error (VPE) ≤ 3.0 m	P	0.06 m
The 95.4th percentile of the cumulative distribution of the VPE ≤ 3.0 m	P	0.11 m
Class III	P	-/-
Accuracy Analysis		
Test Case 2: Rural Recertification: N/A		
Horizontal Position Error (HPE) ≤ 0.50 m	P	0.33 m
The 95.4th percentile of the cumulative distribution of the HPE ≤ 0.50 m	F	1.27 m
Vertical Position Error (VPE) ≤ 2.4 m	P	0.28 m
The 95.4th percentile of the cumulative distribution of the VPE ≤ 2.4 m	F	2.76 m
Class II	F	-/-
Accuracy Analysis		
Test Case 3: Urban Recertification: N/A		
Horizontal Position Error (HPE) ≤ 0.40 m	P	0.34 m
The 95.4th percentile of the cumulative distribution of the HPE ≤ 0.40 m	F	0.87 m
Vertical Position Error (VPE) ≤ 2.0 m	P	0.12 m
The 95.4th percentile of the cumulative distribution of the VPE ≤ 2.0 m	P	1.26 m
Class I	F	-/-

High-Grade Receiver RTK

Certification Mark Possible: Highway!

Conclusions

VaGAD Method

- For the assessment of GNSS devices the same procedures and equipment is used as for operation leading to the same underlying error problems (multipath, shadowing, …).
- Within this project a novel testing method independent of GNSS working principles was developed.
- The VaGAD method is based on tracking and highly accurate positioning of a test vehicle equipped with GNSS receivers using georeferenced aerial imagery.
- Test campaigns where carried out to test the method and evaluate the results.
- Assessment of two types of GNSS devices (automotive-type and an high-grade GNSS receivers) was conducted in the city of Munich and its surroundings.
- The analysis and results of using aerial imagery show that this method can be used as an independent tool for calibration, validation and certification of GNSS devices in real-word environments, e.g., in the highway, rural and urban scenarios.

Conclusions

VaGAD Method

- The observed performance of both receivers is within the expected errors range.
- Even in GNSS denied environments, where GNSS receivers show deviations and gaps the VaGAD method proved to be reliable and resilient.
- It was shown that the positioning using aerial imagery as an independent in-situ method has reached an accuracy of $\sim 10 - 20\ \mathrm{cm}$ necessary to certify GNSS receivers aiming at high accuracy performance levels.
- Therefore the VaGAD method is suitable for GNSS DUT calibration, validation and certification activities.

Conclusions

Commercialization and Dissemination

- The VaGAD is the result and cross-fertilisation between several PNT technologies, applied to certification, validation and testing offered as a service.
- The VaGAD method is mature and can respond to the needs of the PNT market. Therefore, as a service it is ready to be explored commercial.
- Commercialization agreement between DLR and NavCert.
- The service has the following advantages:
  - Provision of reference data for GNSS based receiver in the scope of automated driving
  - Provide guidance how a GNSS receiver may be validated even in critical scenarios
  - Provide accurate reference data in real world scenarios Rural/Highway/Urban
- We will share the key benefits of the new service with our established network in the automotive industry and participate in exhibitions, and congresses.