Analysis and calibration of the VLP-16 for automotive applications

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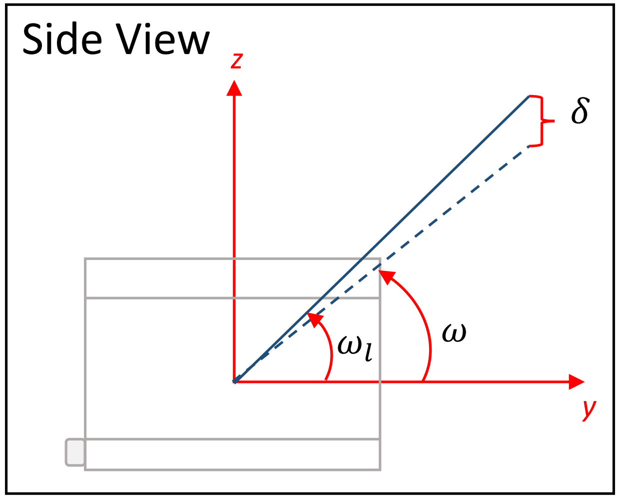
ION GNSS+ 2019

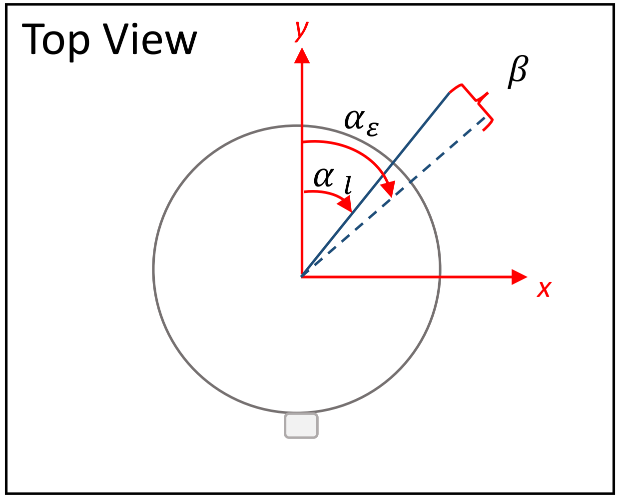
Outline

- Introduction
- Previous work
- Calibration setup
- Data processing
- Results
- Conclusions

Introduction I

- **Many terrestrial laser scanner applications, and specifically precise localization for autonomous driving using LiDAR, demand accurate and precise measurements.**
- **Systematic errors can be found in the instrumentation due to imperfections during the manufacture and assembly of the sensor.**
- **Parameters that can be modeled for this specific sensor are (interior calibration):**
  - Vertical and horizontal rotation correction (δ_i , β_i)
  - Vertical and horizontal offset (H_0^i, V_0^i)
  - Distance offset (D_0^i)
  - Distance scale factor (s_i)





Previous work I

- **Previous analysis (Lichti & Glennie) have performed a planar feature based least-square adjustment to find the internal calibration parameters**
  - The performance of individual lasers is not uniform.
  - Temporal instablity (VLP-16): stability of measurements during long-term recordings
  - Temperature instability (HDL-64E): effect of temperature variations and time needed to get into a steady state
- **They demonstrated that their sensor fulfills the manufacturer's stated accuracy of its specifications**
  - To take in to account that the data is collected at short ranges to the target
  - It is highlighted that some laser channels behave significantly poorer than others
- **Therefore, the present work shows the methodology we used to evaluate the performance of each laser channel and characterize them independently of each other.**
- **Moreover, we evaluate the measurements of the sensor in a wider span of ranges**
  - From 1 m up to 20 m

Calibration setup

- **Manufacturer specifications for the VLP-16 Puck**

Sensor	16 lasers
	FOV-V: 30° (+15° to -15°)
	FOV-H: 360 °
	3 cm accuracy
Laser	Class 1
	903 nm wavelength
	3.0 mrad horizontal beam divergence
	1.5 mrad vertical beam divergence

- **Configuration used during measurements**

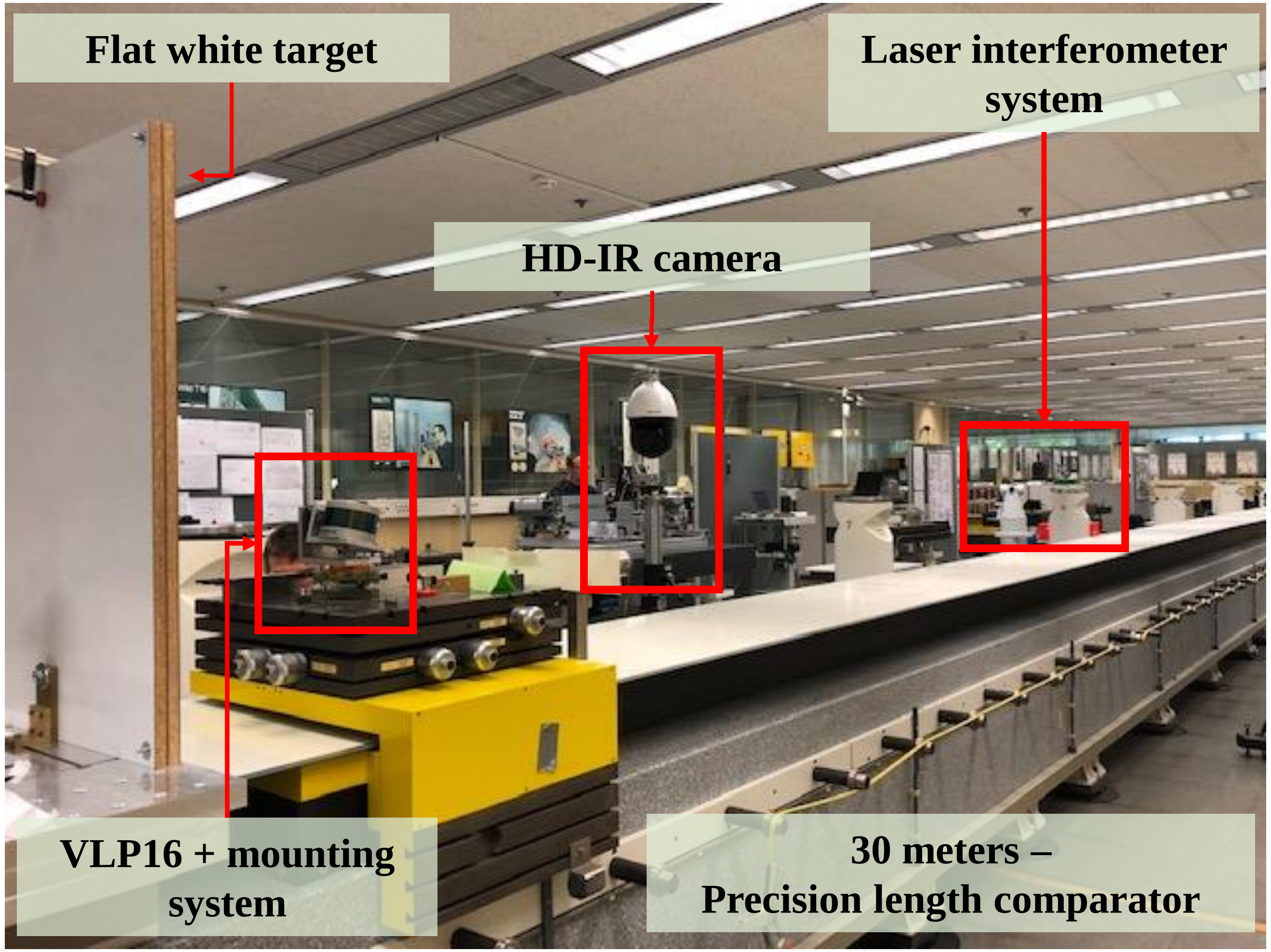
Rotation rate	10 Hz
Return mode	Strongest
Phase Lock	off

Calibration setup II

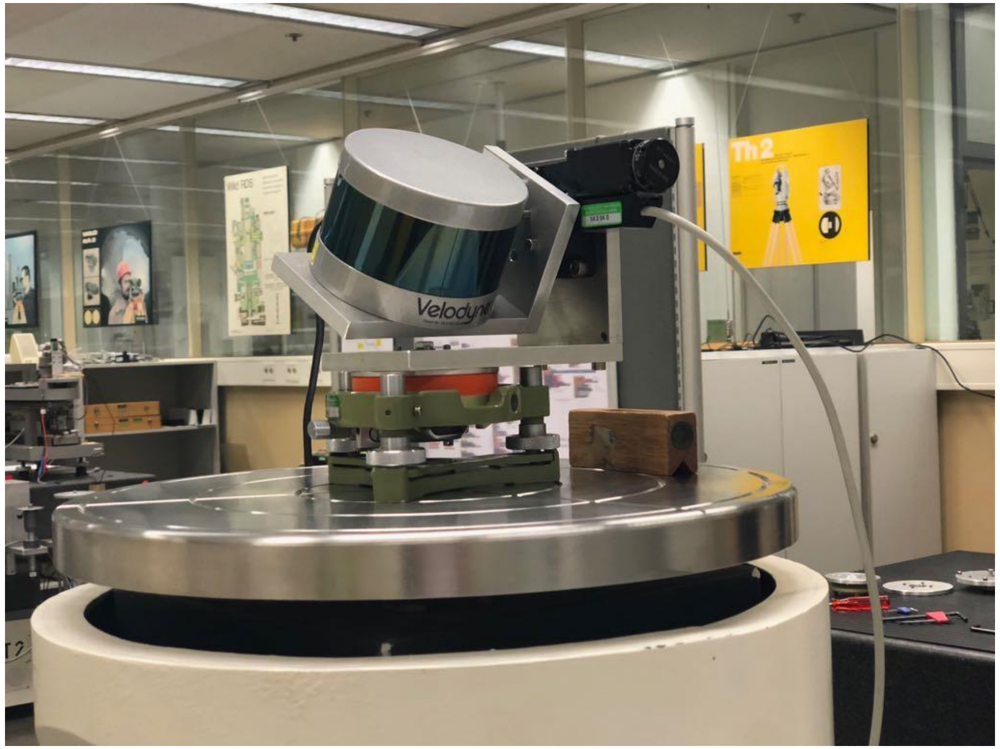
Measurements at:

1 m, 2 m, 4 m, 6 m, 8 m

10 m, 12.5 m, 15 m, 17.5 m, 20 m



Calibration setup II



VLP-16 mounting

- To steer electronically the laser channels of the sensor and thus, have control of the direction in which the lasers intersect the surface of the target
- A rotation is applied around the x-axis of the sensor
- Maximum accuracy of the applied rotation is 1/20 of a degree
- Approximately the duration of each recording is 20s
- Before the measurements 30 minutes to warm up the sensor and get to a steady state
- The sensor was never powered off during the measurements

Calibration setup III

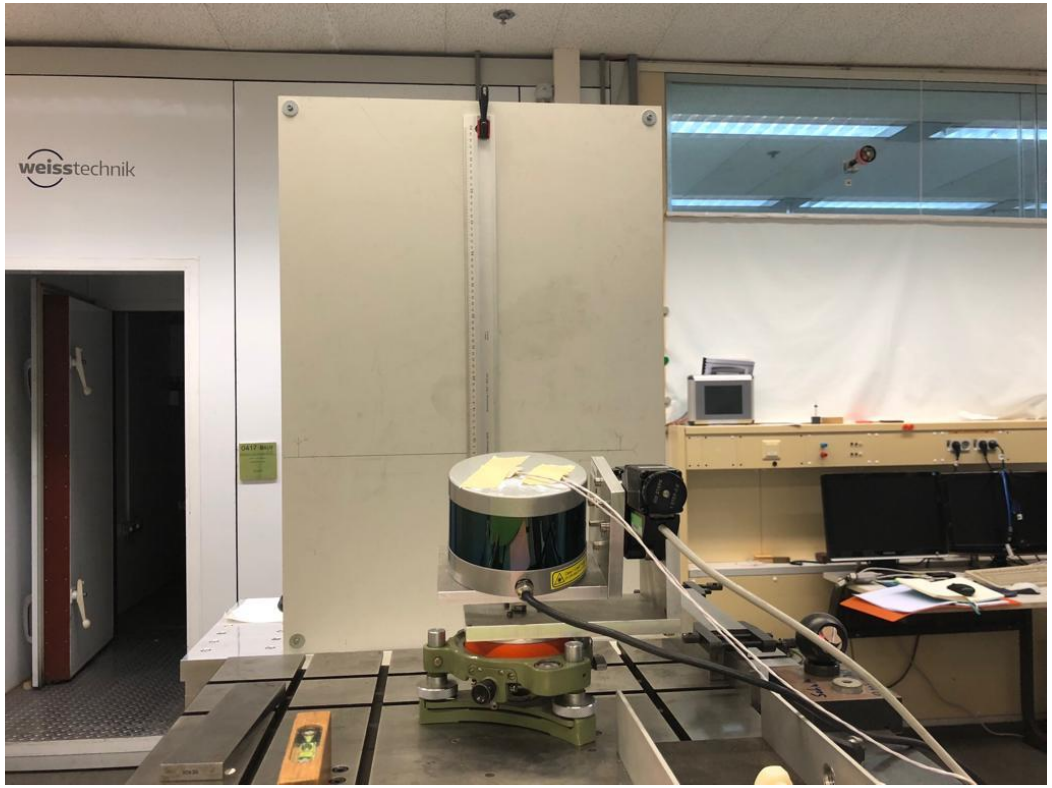
HD-IR camera [left]

- **Used to visualize the lasers on the surface of the target and apply the correct pitch to align the laser to the xy-reference plane of the sensor**

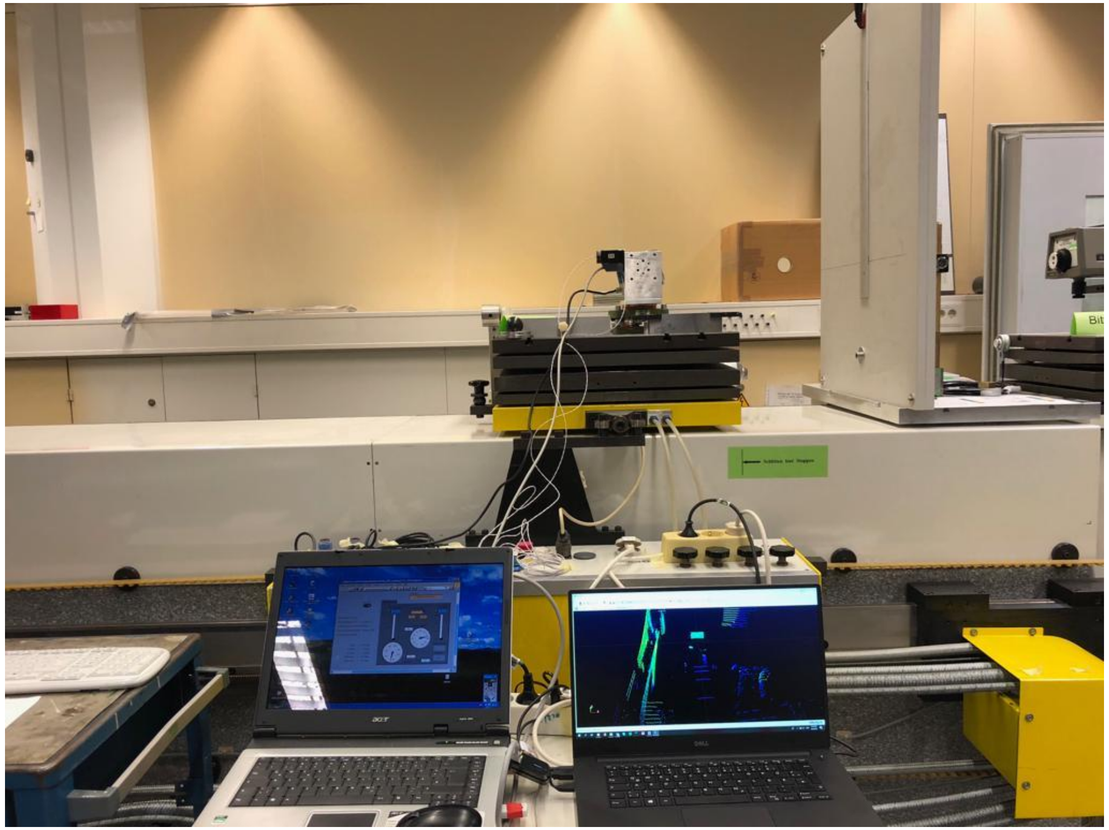
Laser interferometer [right]

- **Used to place the sensor at a specific distance from the target**
- **It has an automatic line of capture with an uncertainty of 0.6 μm**

Calibration setup IV



Front view (sensor's perspective)



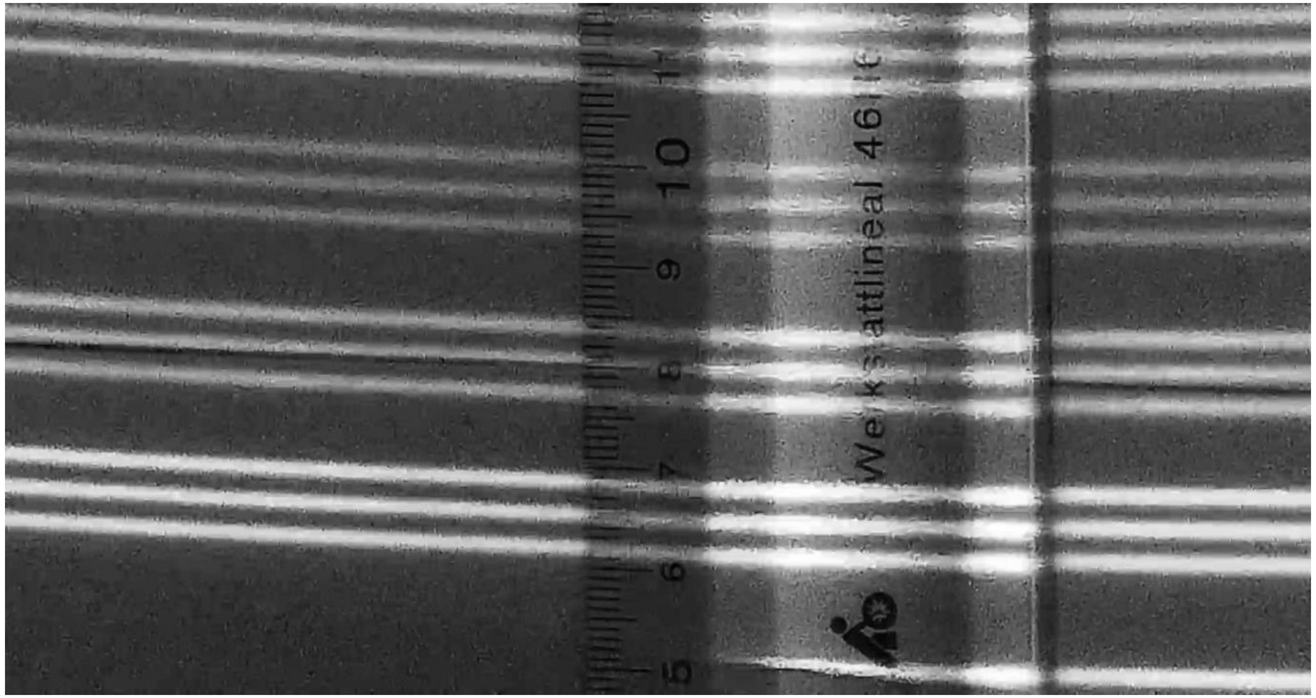
Lateral view

Calibration setup

V

Sample picture from the HD-IR camera

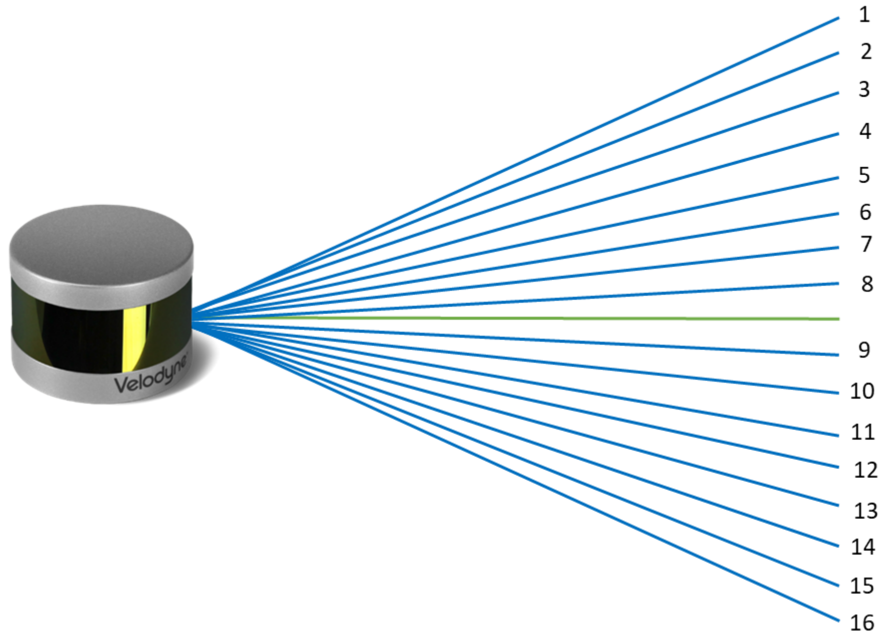
- **Each triad comes from each of the 16 lasers that are integrated in the sensor.**
- **For each triad, the one in the middle was taken as reference to align the lasers to x-y reference plane.**
- **To choose the right pitch to apply to each laser, measurements were done at: 0.75m, 1m, 2m.**



Laser spot pattern (Stacked laser diodes)

Calibration setup

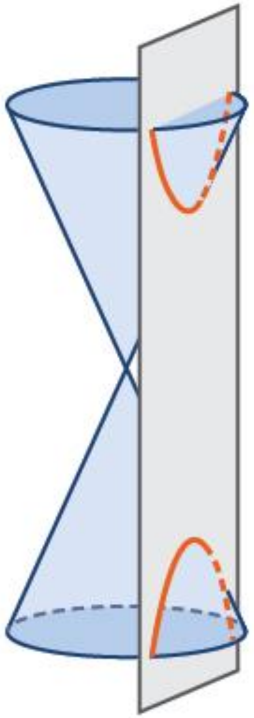
Channel	Theoretical El [deg]	El @ 0.75m [deg]	El @ 1m [deg]	El @ 2m [deg]	Hz resolution [deg]	Symmetry
1	**15**	14.71	14.35	**14.70**		
2	**13**	12.30	12.45	**12.75**	1.95	
3	**11**	10.40	10.55	**10.80**	1.95	
4	**9**	8.50	8.65	**8.85**	1.95	
5	**7**	6.40	6.55	**6.75**	2.10	
6	**5**	4.50	4.65	**4.85**	1.90	
7	**3**	2.80	2.85	**2.95**	1.90	
8	**1**	0.80	0.85	**0.95**	2.00	
9	**-1**	-1.00	-1.05	**-1.00**	1.95	
10	**-3**	-2.90	-2.95	**-2.95**	1.95	
11	**-5**	-4.90	-4.95	**-4.95**	2.00	
12	**-7**	-6.70	-6.80	**-6.90**	1.95	
13	**-9**	-8.55	-8.75	**-8.85**	1.95	
14	**-11**	-10.45	-10.65	**-10.80**	1.95	
15	**-13**	-12.45	-12.65	**-12.80**	2.00	
16	**-15**	-14.25	-14.45	**-14.70**	1.90	

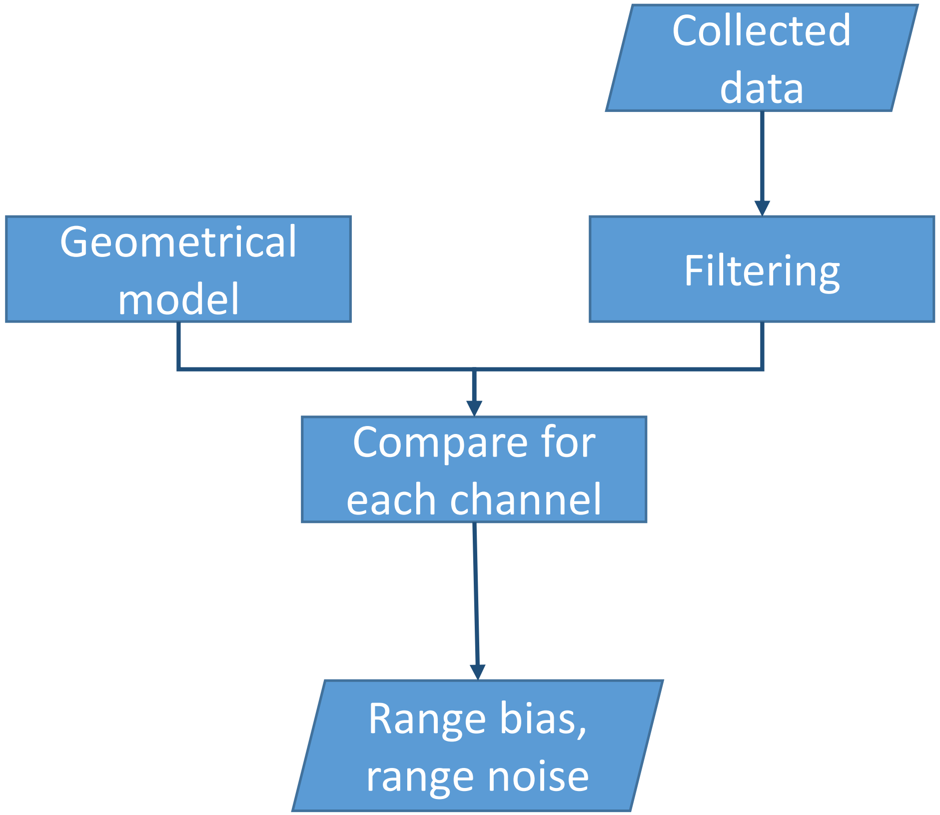


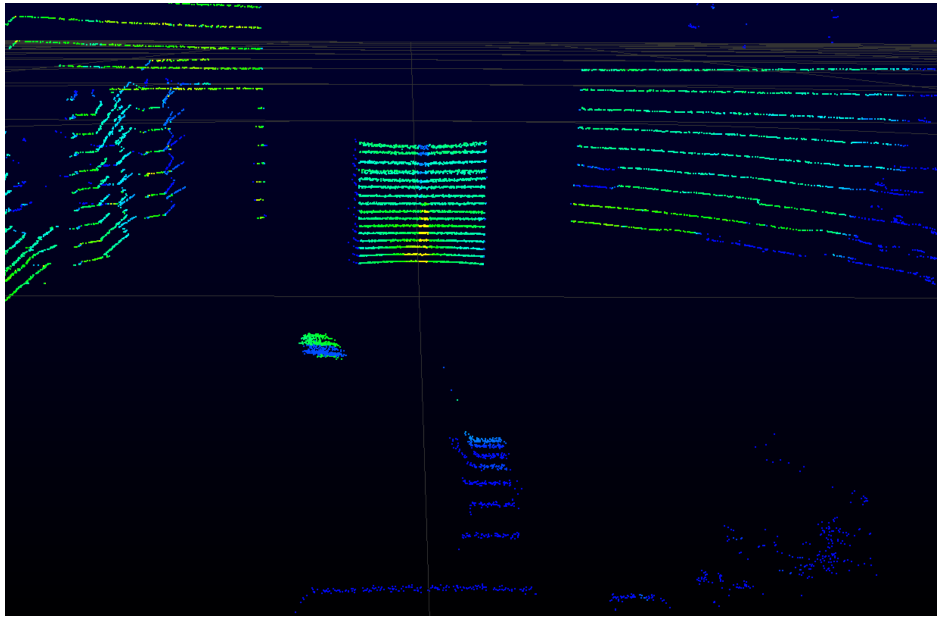
Red	>= 0.1 deg
Orange	< 0.1 deg
Green	same value

Data Processing

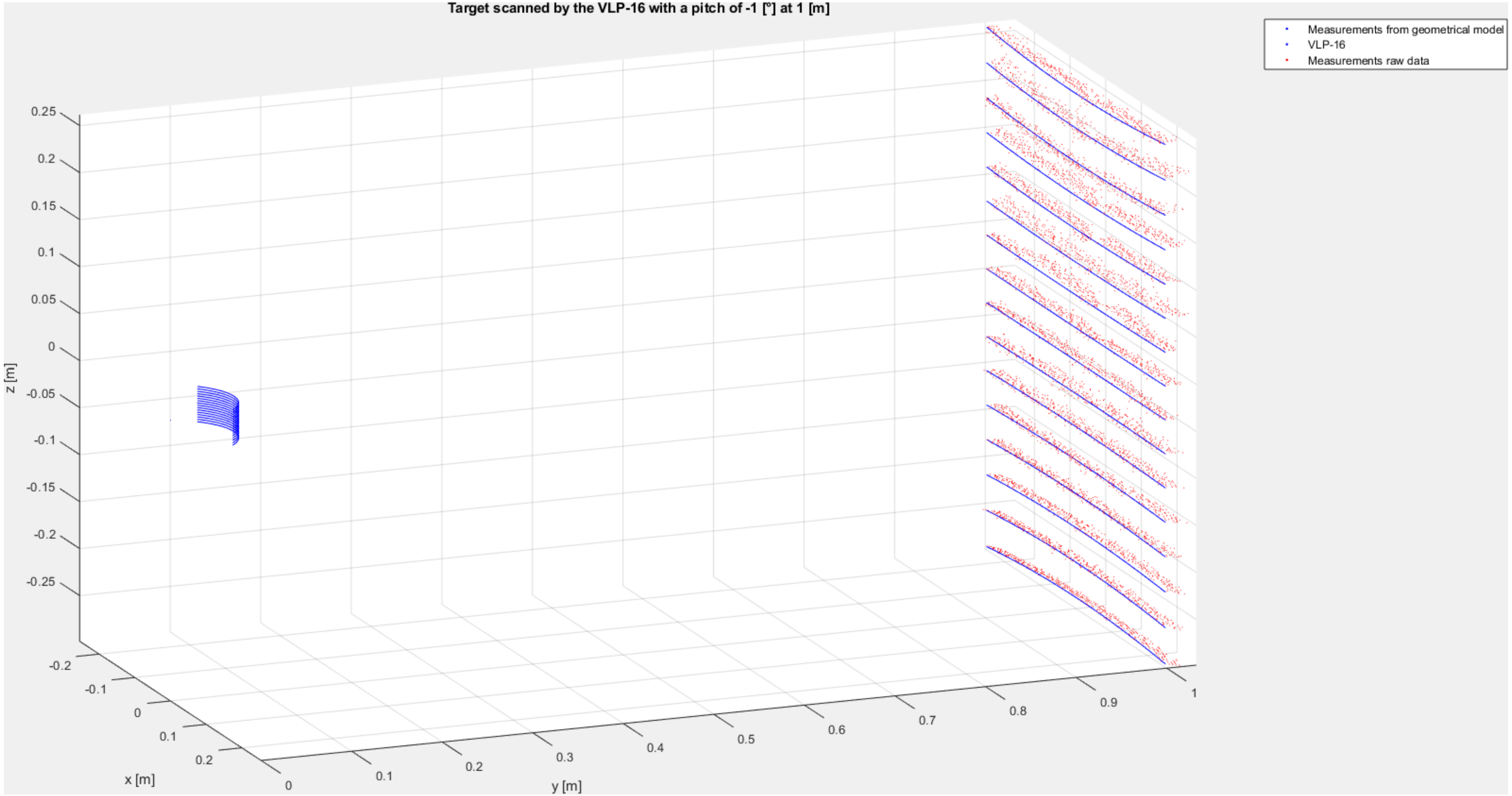
I





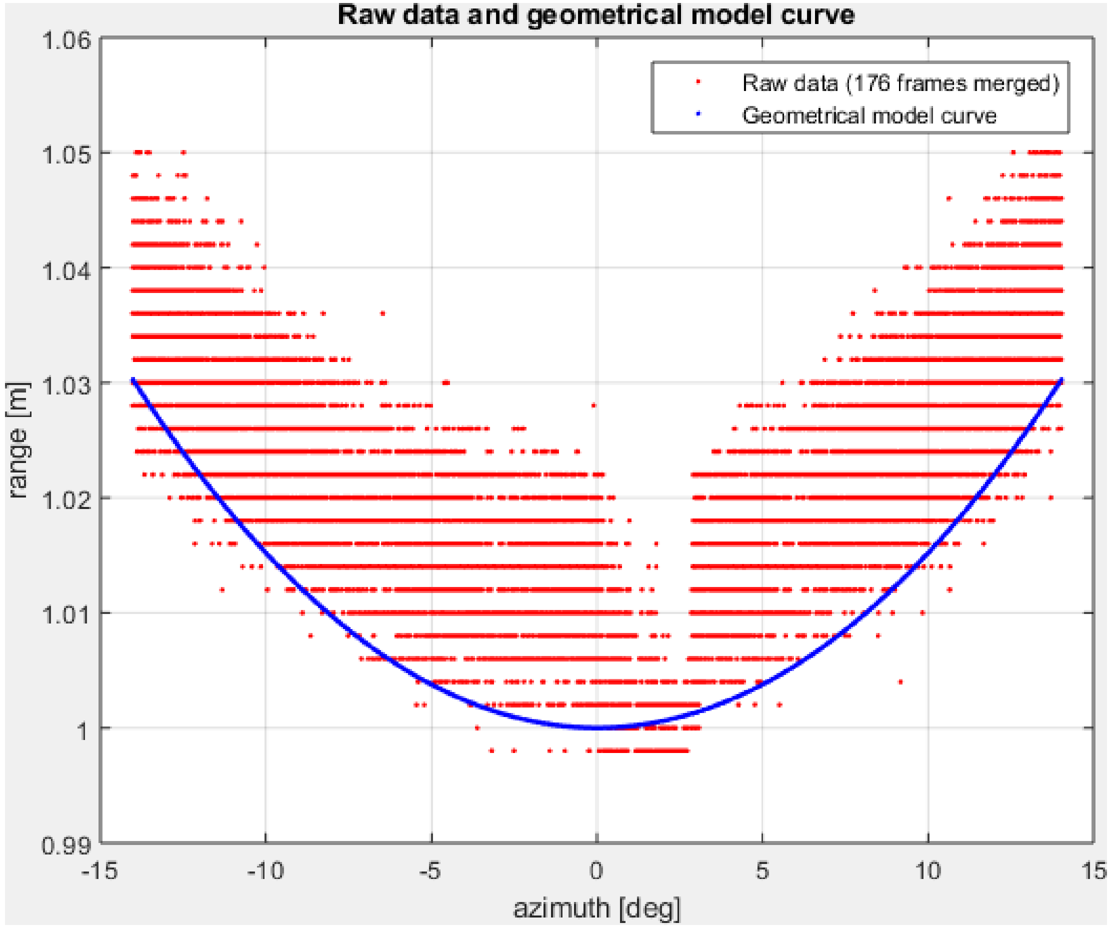


Data Processing II

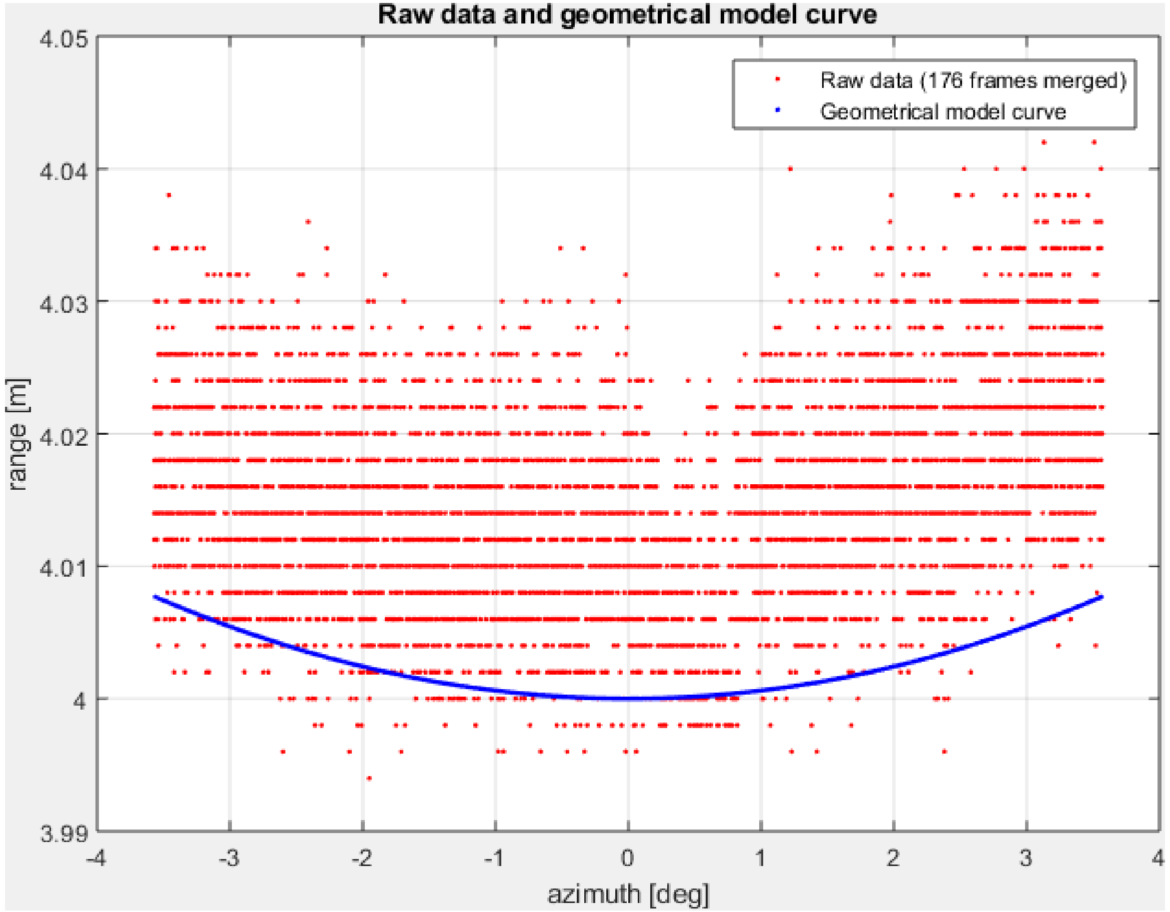


Preliminary results I

Channel 5 at 1m

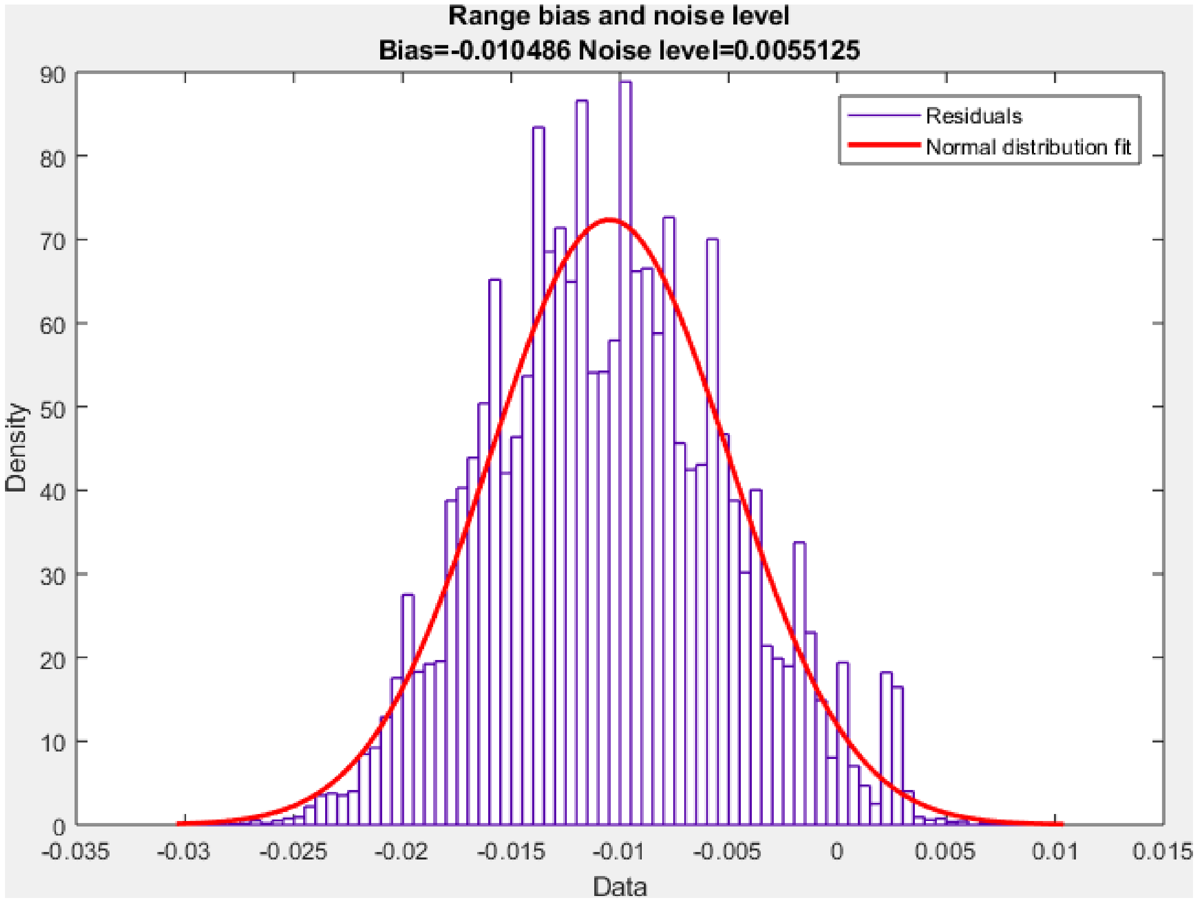


Channel 6 at 4m

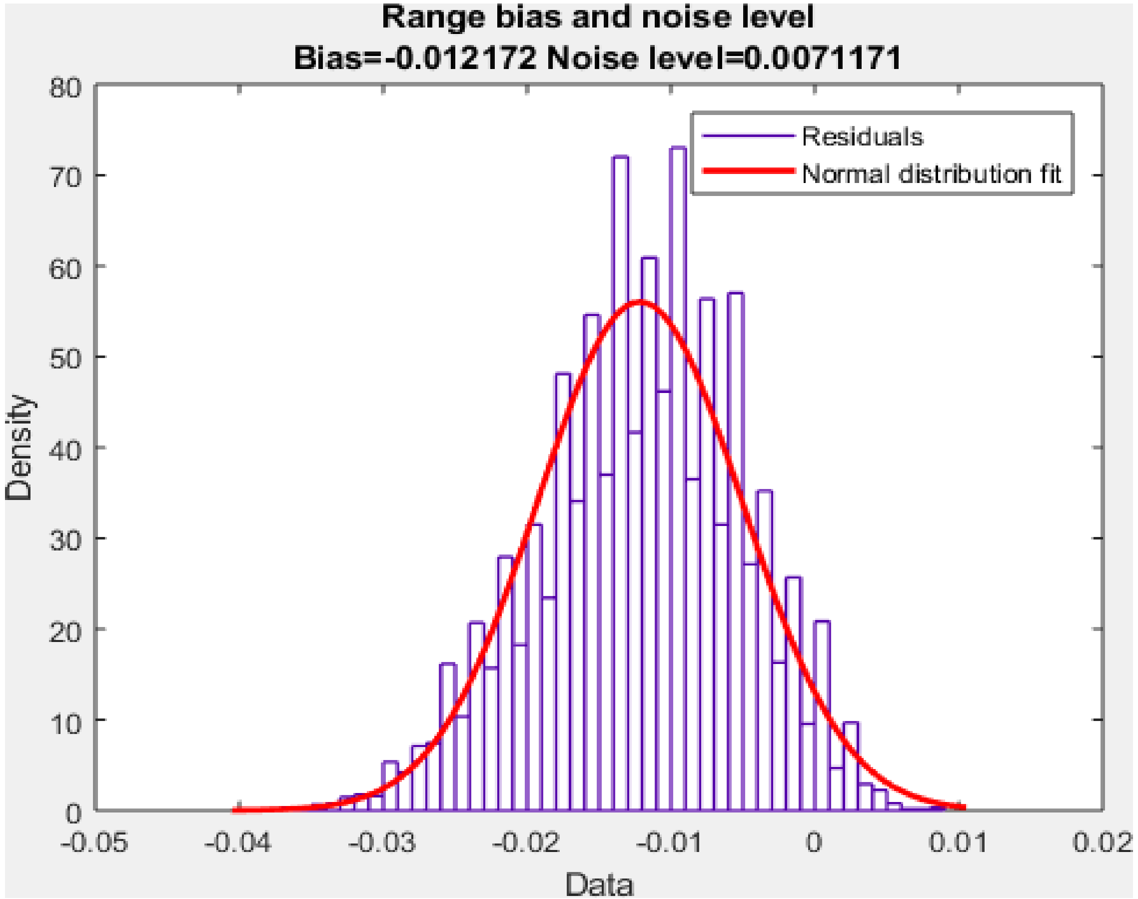


Preliminary results II

Channel 5 at 1m

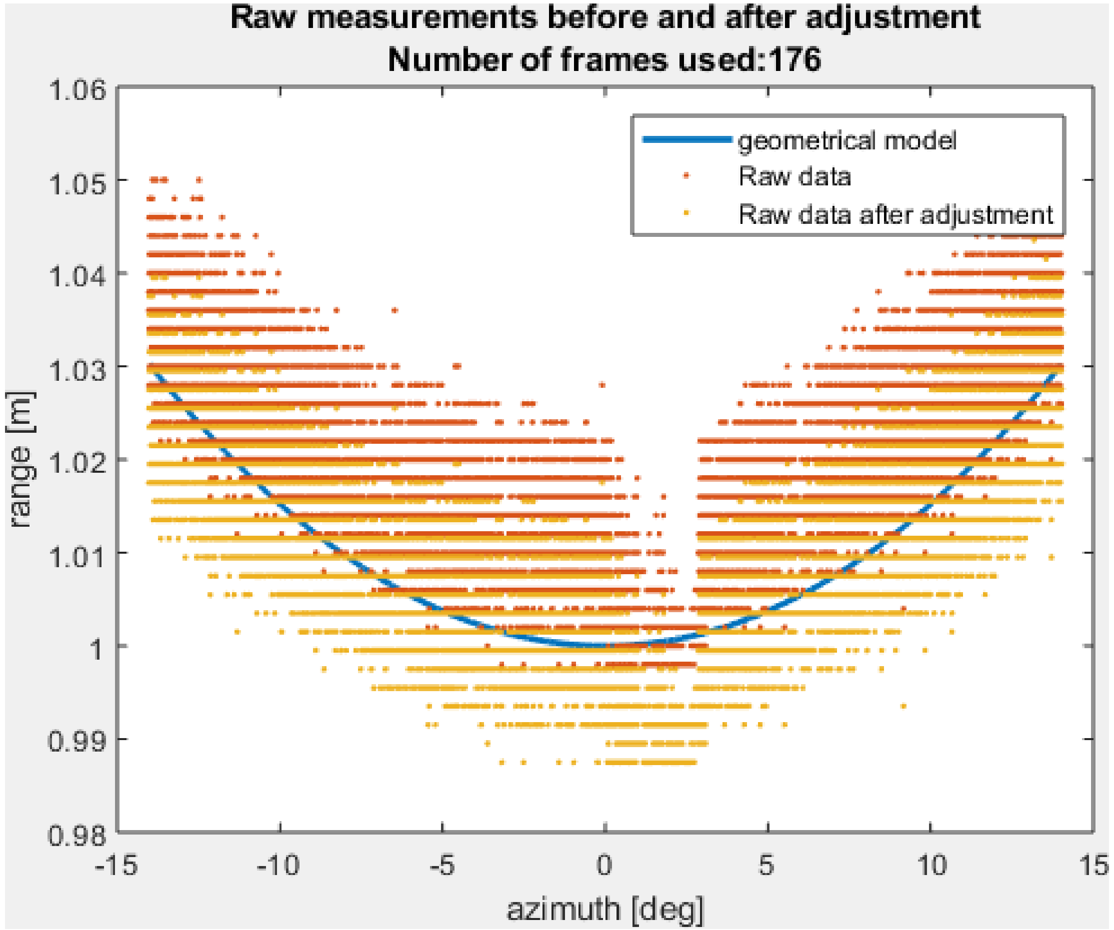


Channel 6 at 4m

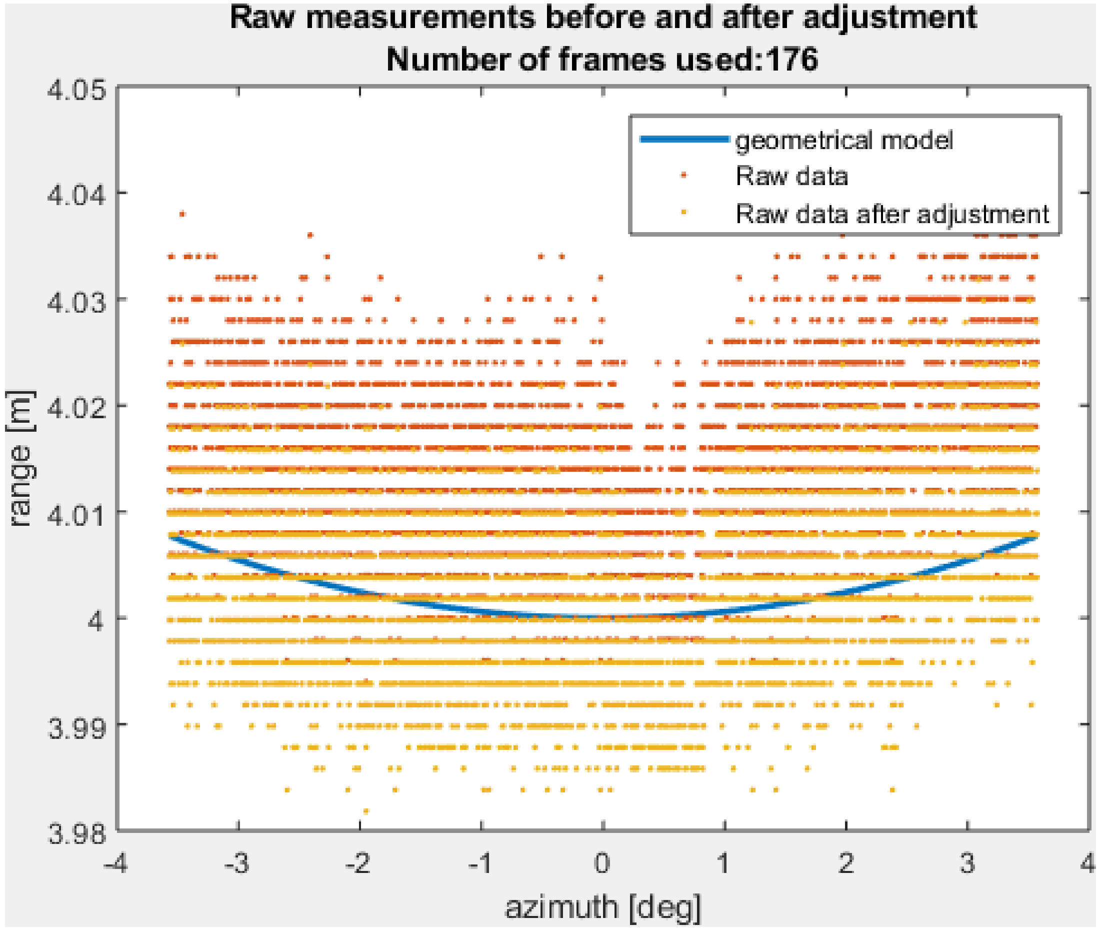


Preliminary results III

Channel 5 at 1m



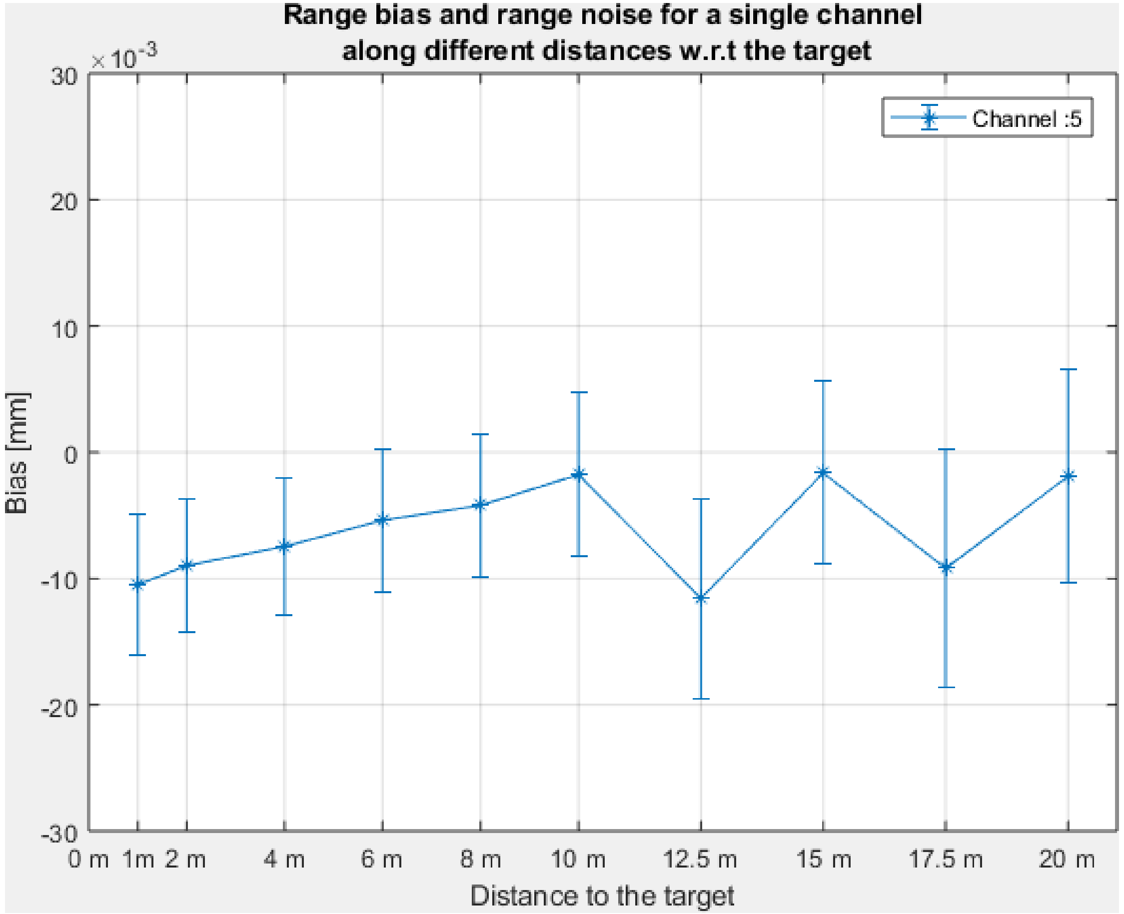
Channel 6 at 4m



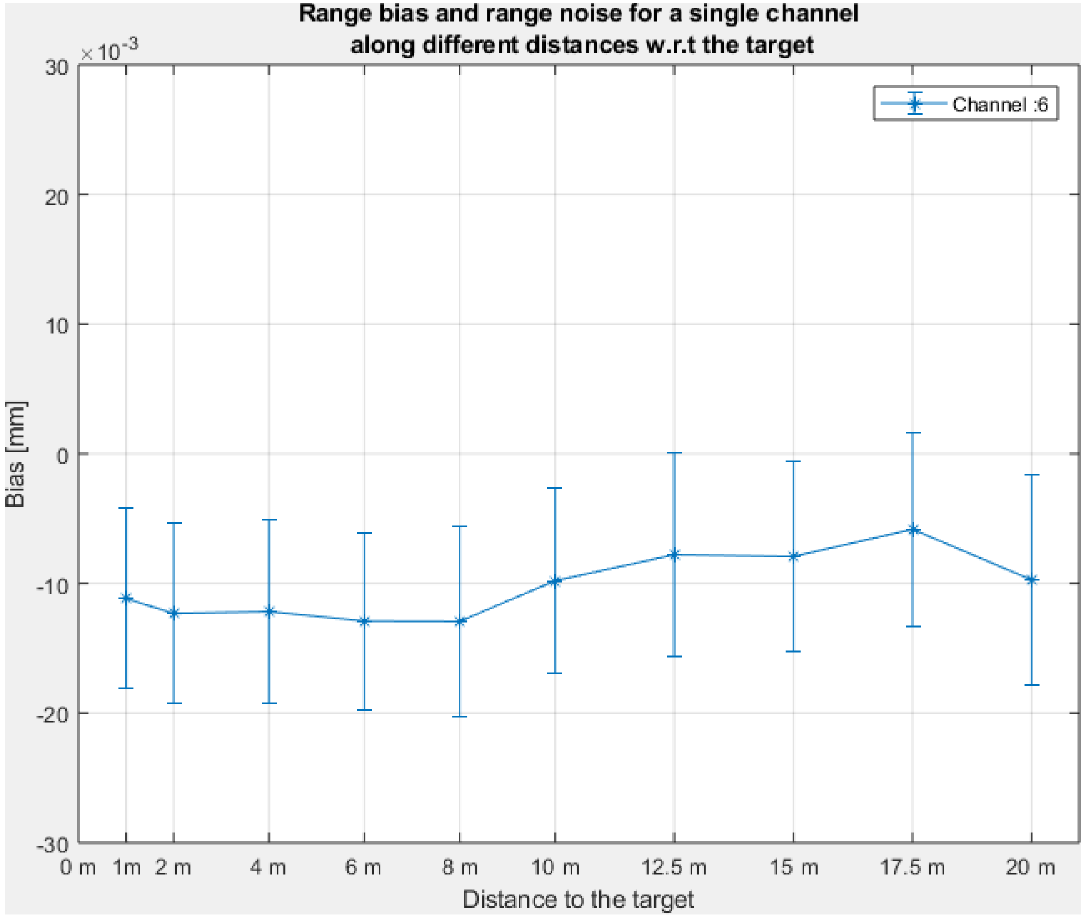
Preliminary results

IV

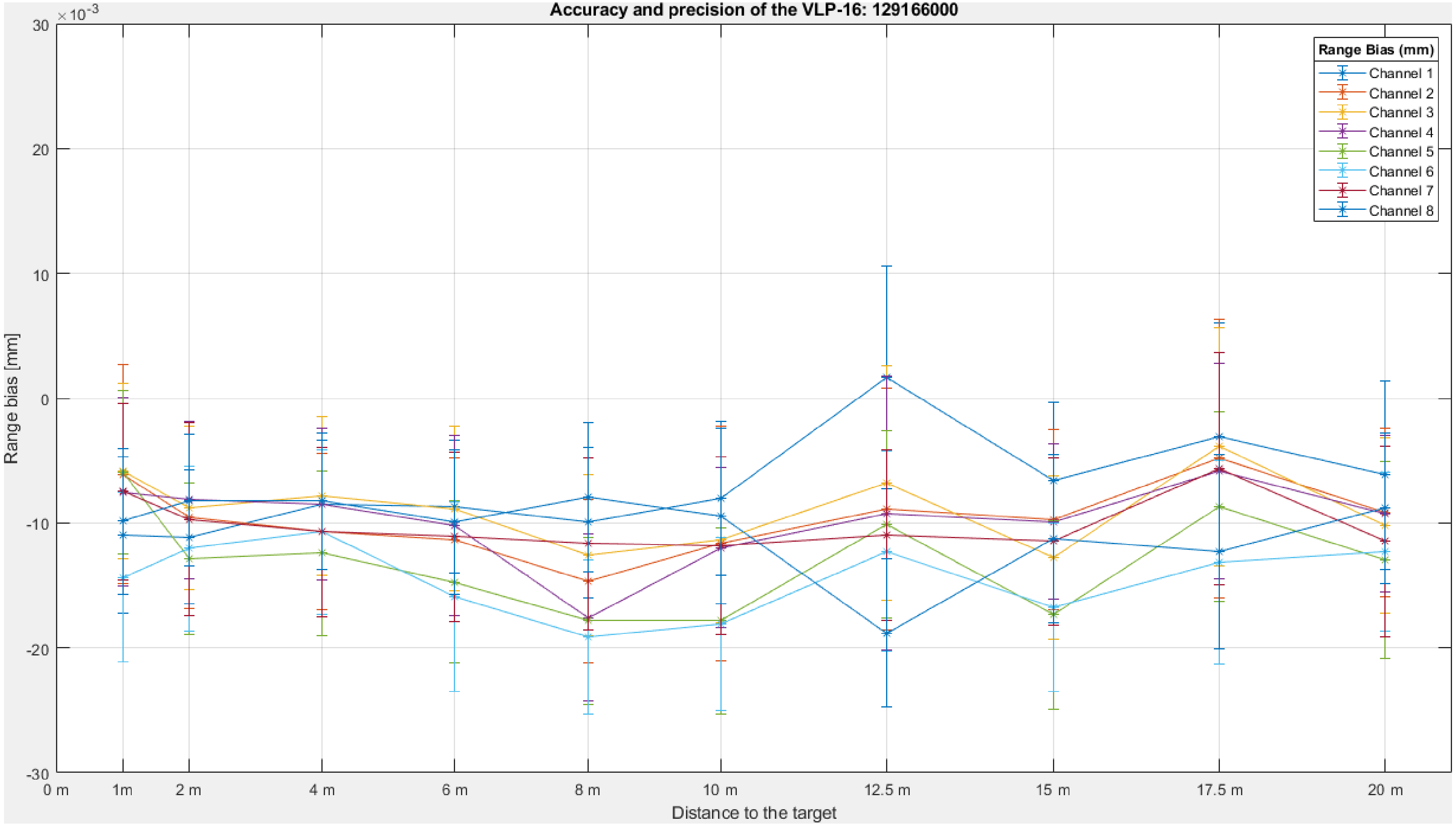
Channel 5



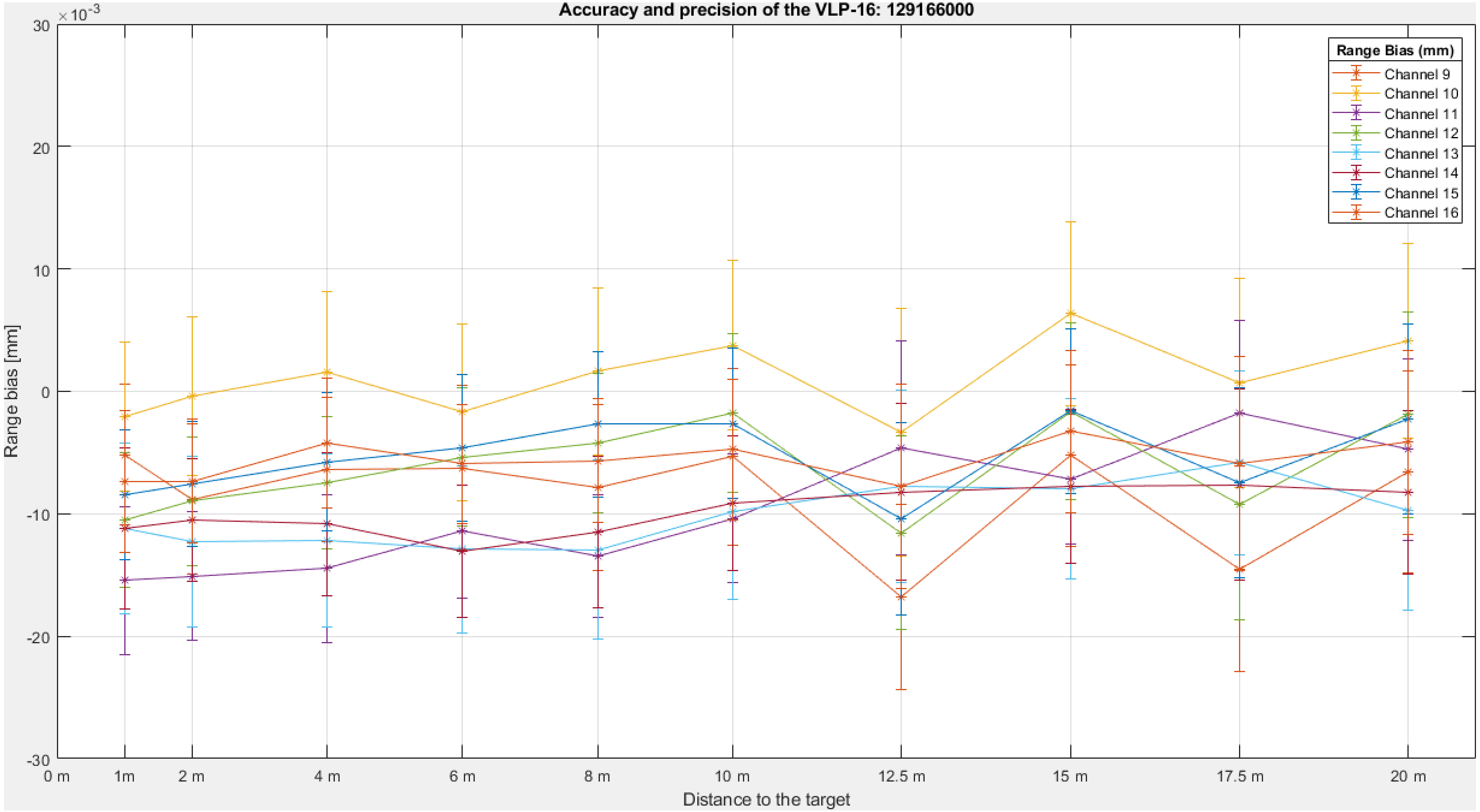
Channel 6



Results


Accuracy and precision of the VLP-16: 129166000
× 10^-3
30
20
10
0
-10
-20
-30
Range bias [mm]
0 m
1m
2 m
4 m
6 m
8 m
10 m
12.5 m
15 m
17.5 m
20 m
Distance to the target
Range Bias (mm)
Channel 1
Channel 2
Channel 3
Channel 4
Channel 5
Channel 6
Channel 7
Channel 8

Results II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0
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-30
0 m
1m
2 m
4 m
6 m
8 m
10 m
12.5 m
15 m
17.5 m
20 m
Distance to the target
Range Bias (mm)
Channel 9
Channel 10
Channel 11
Channel 12
Channel 13
Channel 14
Channel 15
Channel 16

Conclusions I

- **Fulfills the specifications of the sensor**
- **Agrees with previous work done by Lichti and Glennie**
  - Range noise vary from 5-12 mm
  - Maximum range bias of 20 mm
- **Contrary to Lichti, the lasers that were looking more downward were not performing worse than the others.**
- **A correction can be applied to enhance the accuracy of the measurements, although it not may be significant for automotive applications**
- **The biggest disadvantage is the noise in the data (due to the mechanical moving parts)**
- **To inquire:**
  - Relationship between reflection properties of targets and range measurements

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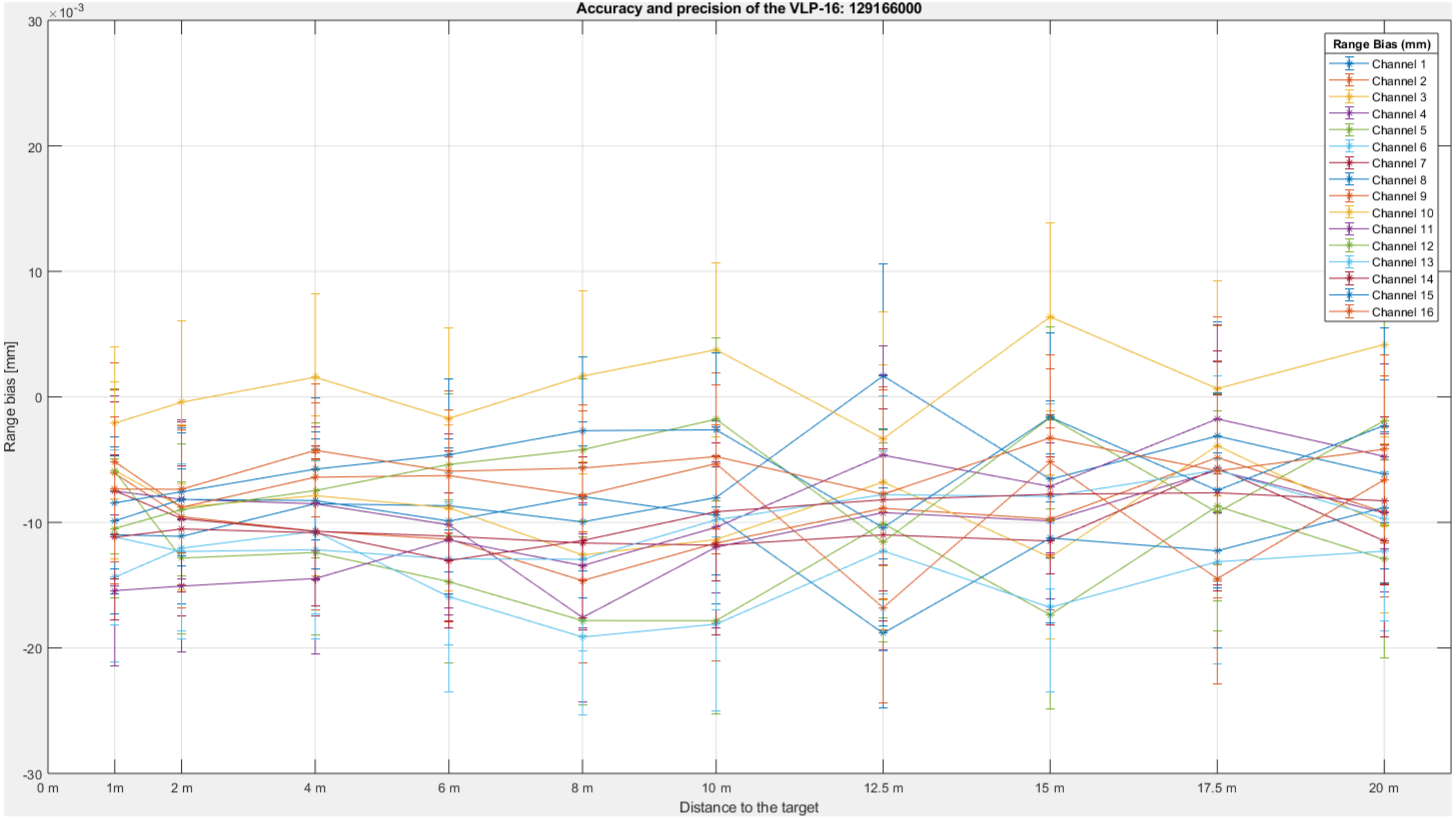
Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Additional material

Results III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Channel 8
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Channel 10
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Channel 13
Channel 14
Channel 15
Channel 16

Other systematic errors (artifacts) I

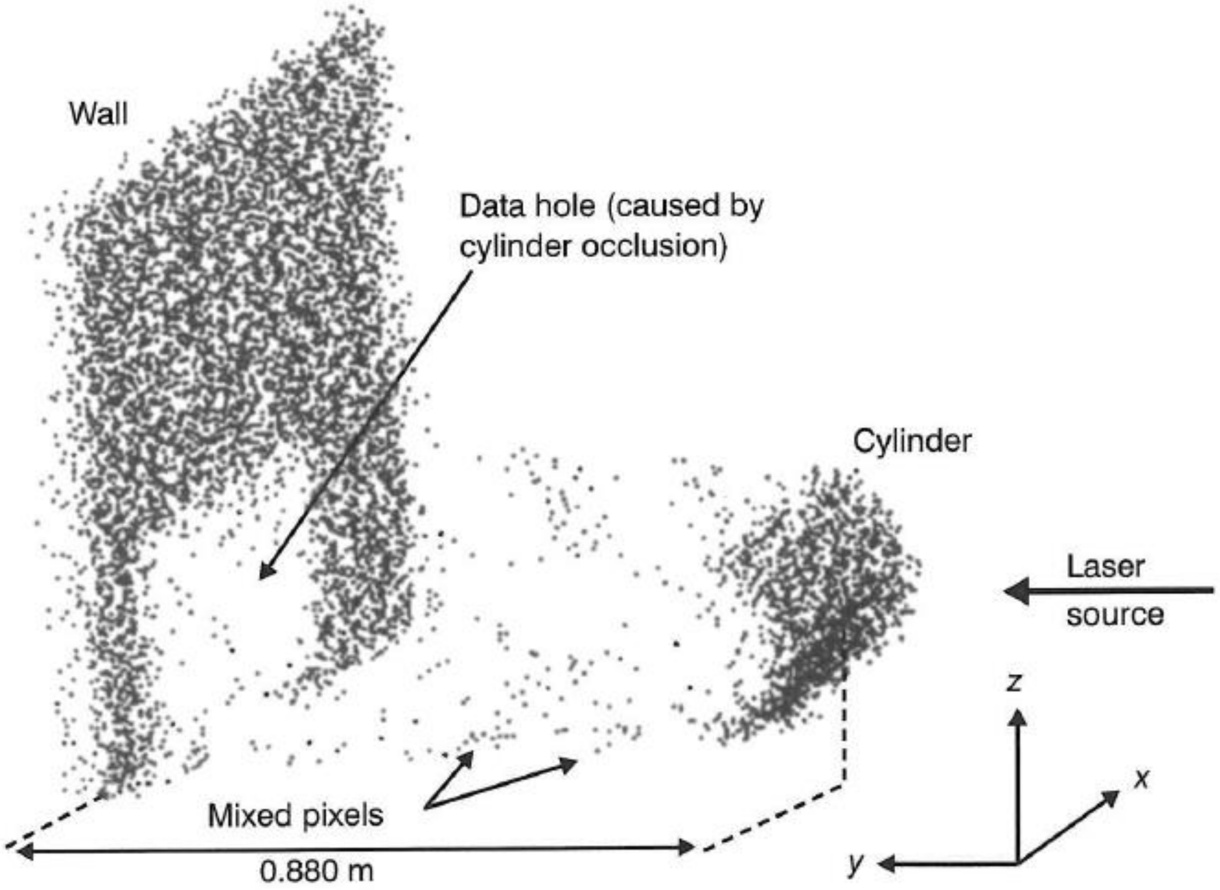


Figure . Subsystem error contribution (without GPS) to target error for a terrestrial vehicle system (LMS-Q240). (Imagen taken from Glennie,2007)

Other systematic errors (artifacts) II

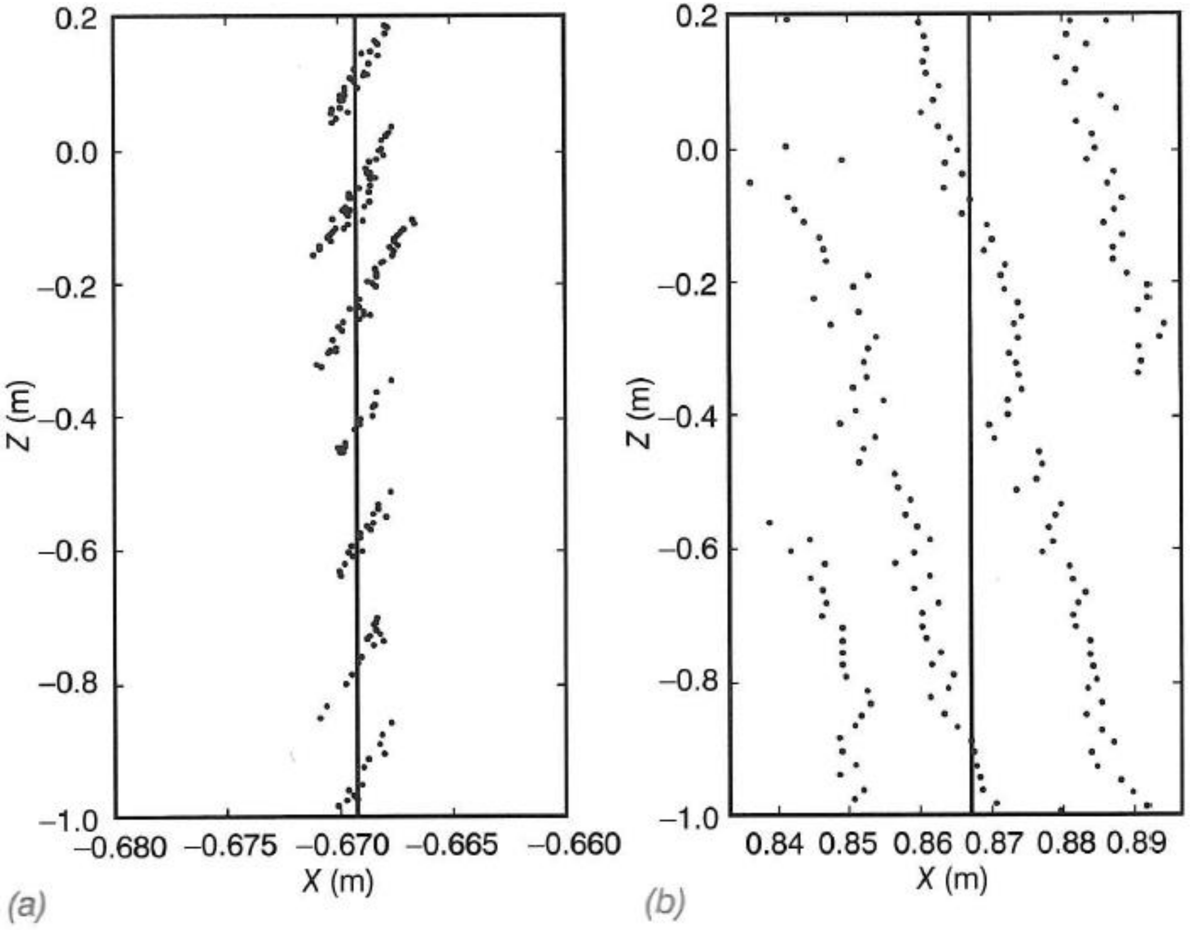


Figure . Subsystem error contribution (without GPS) to target error for a terrestrial vehicle system (LMS-Q240). (Imagen taken from Glennie,2007)

Other systematic errors (artifacts) III

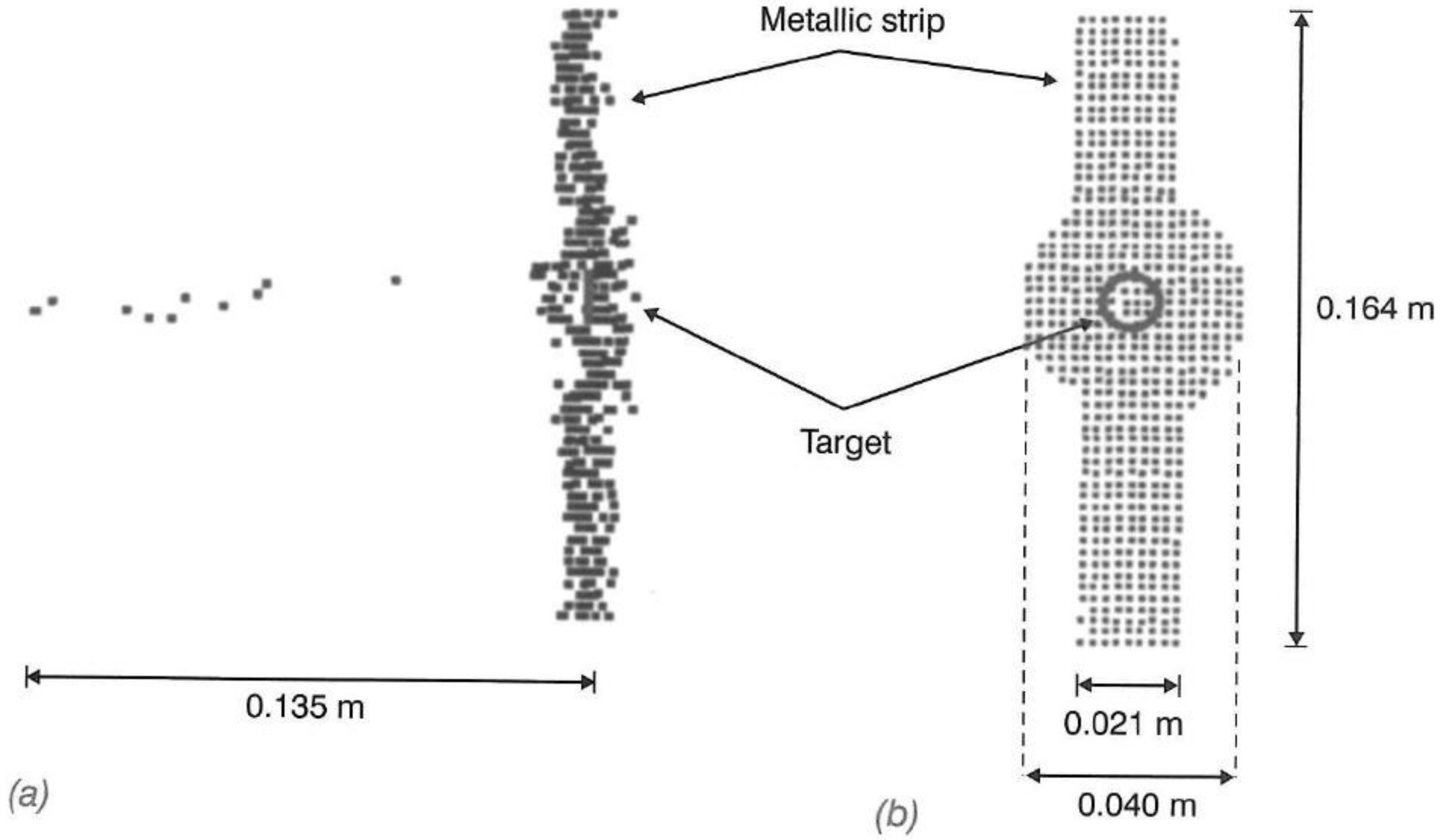
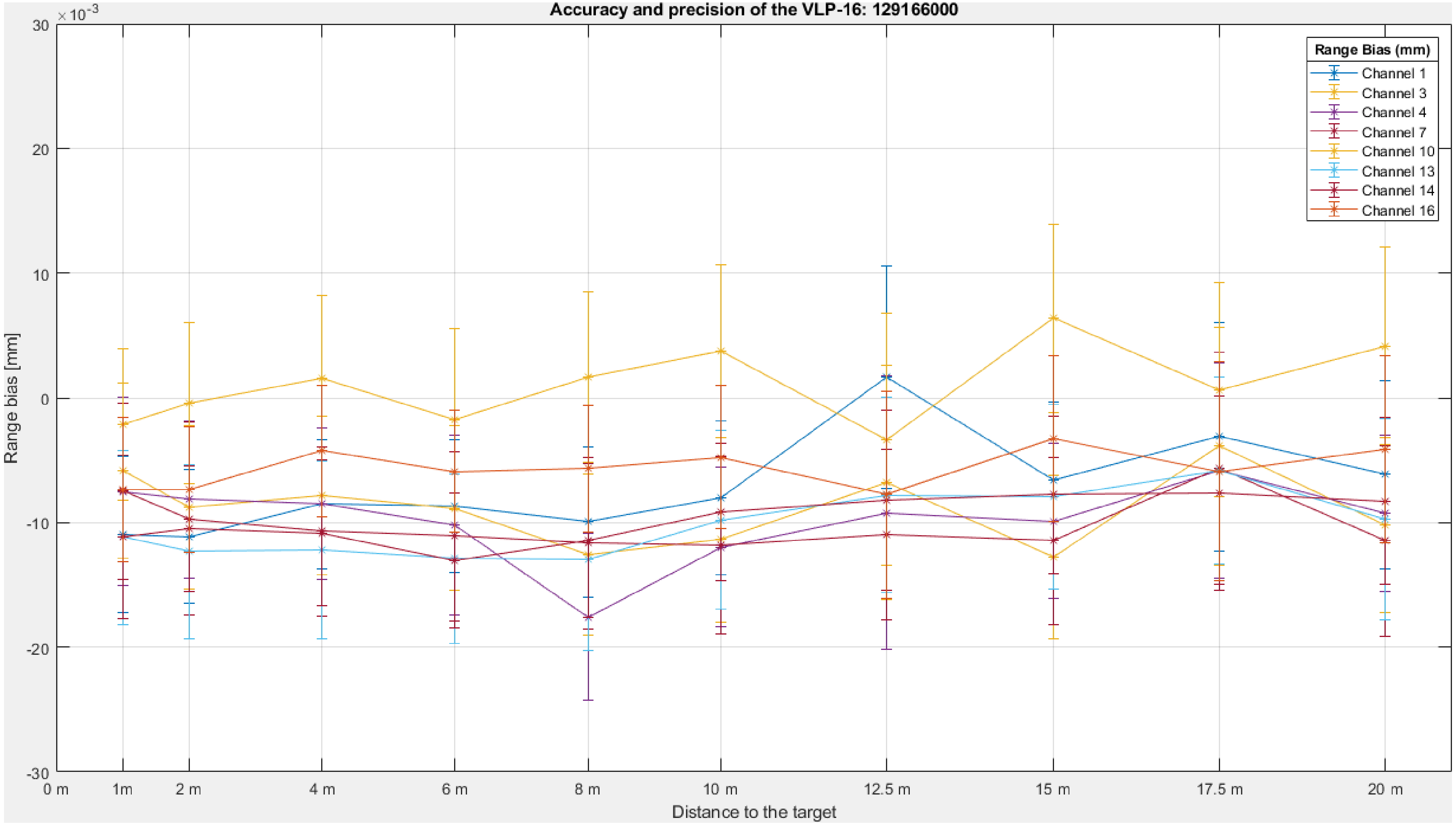
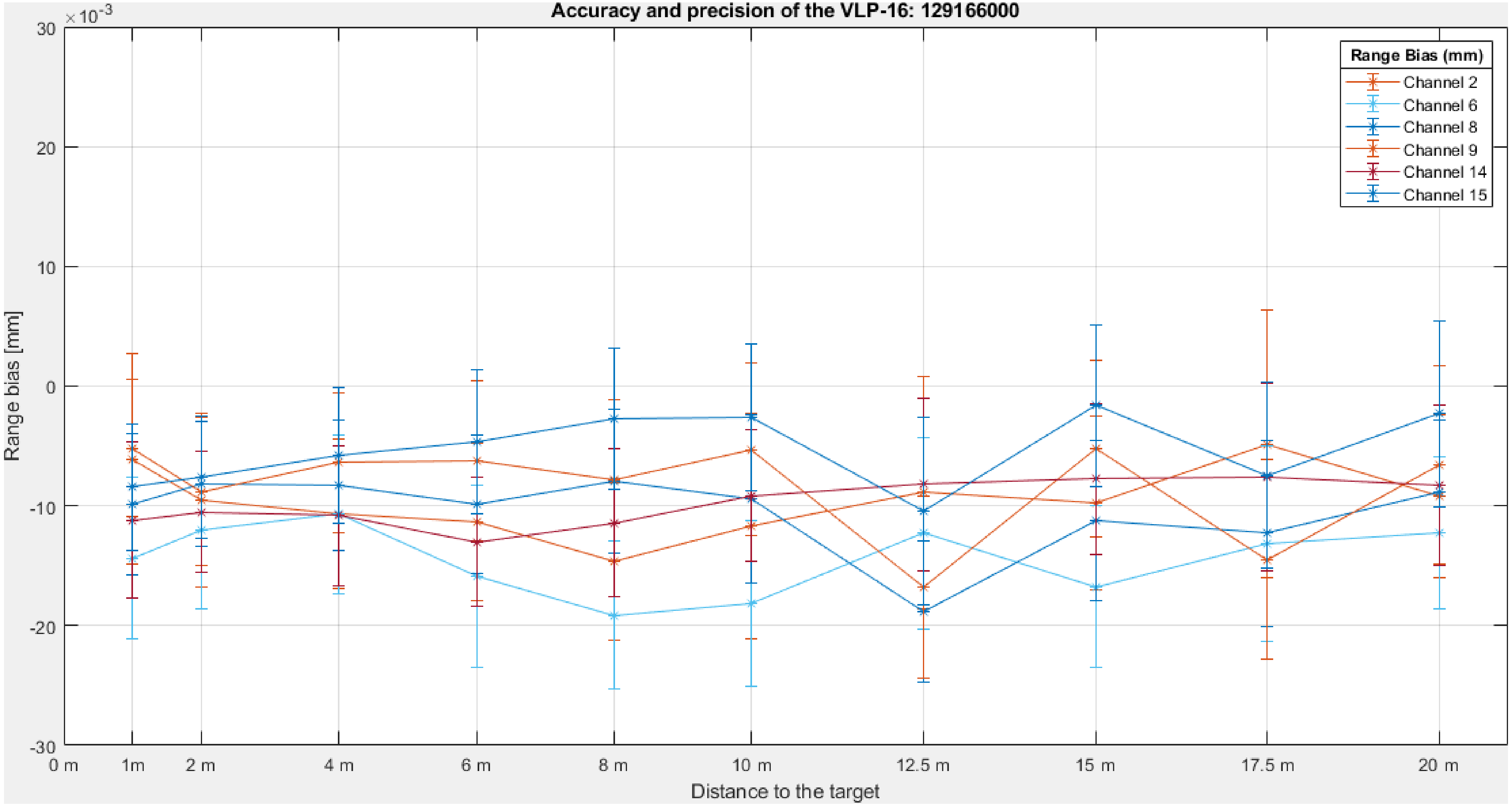


Figure . Subsystem error contribution (without GPS) to target error for a terrestrial vehicle system (LMS-Q240). (Imagen taken from Glennie,2007)

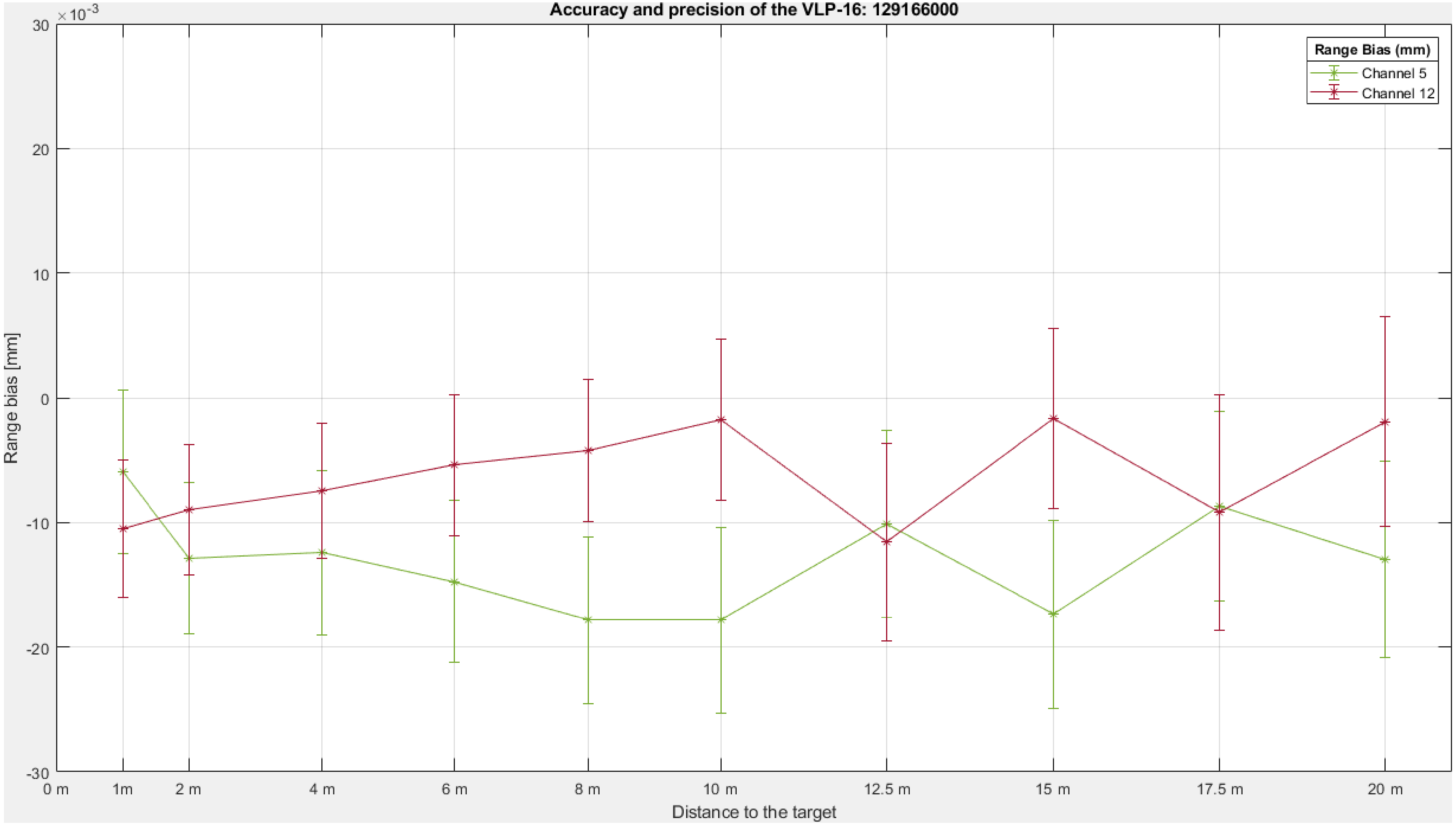
Range bias and noise (g)



Range bias and noise (σ) II



Range bias and noise (r) III



Target accuracy error budget

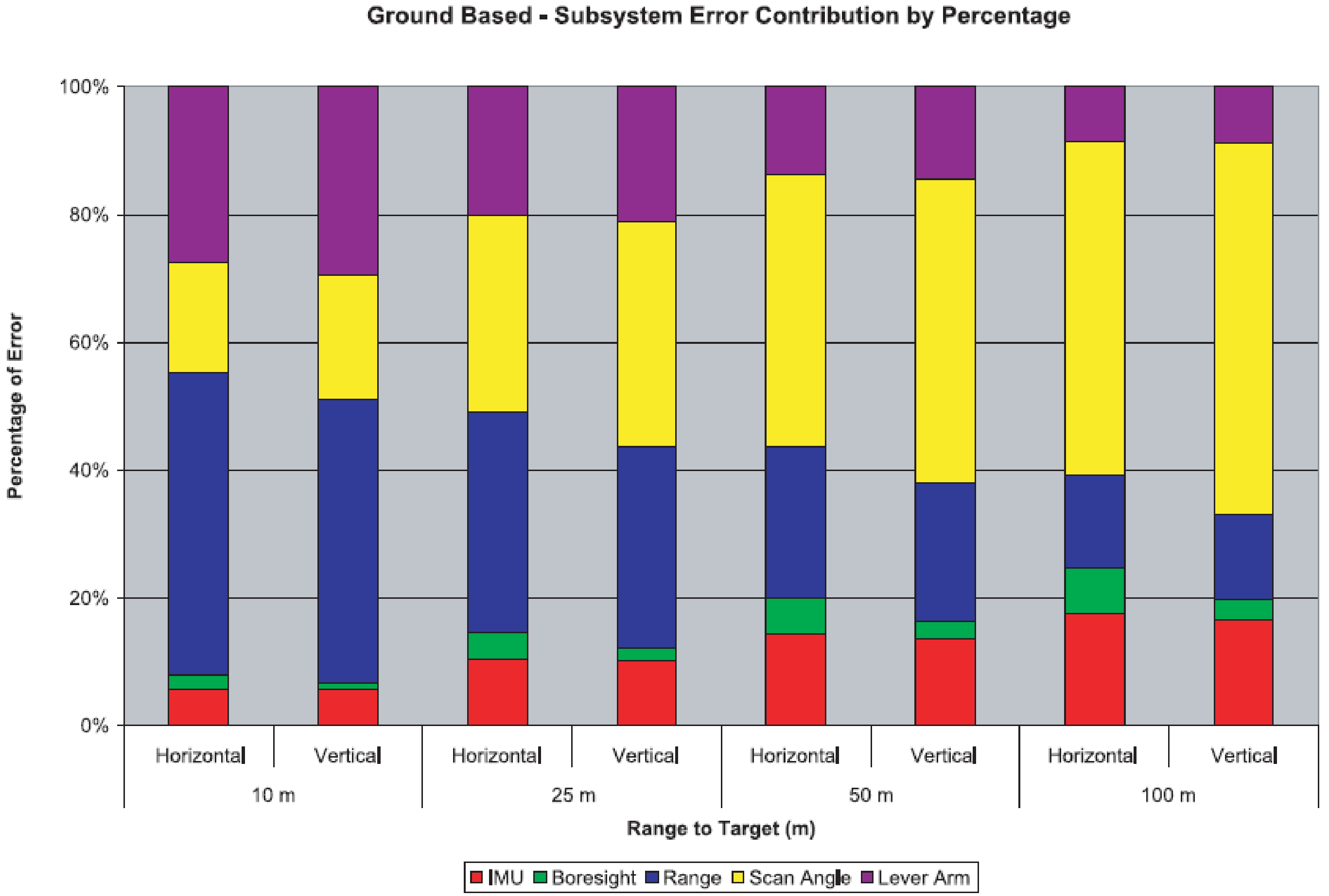


Figure . Subsystem error contribution (without GPS) to target error for a terrestrial vehicle system (LMS-Q240). (Imagen taken from Glennie,2007)

Other systematic errors (artifacts)

$$\Delta\rho = A_0 + A_1\rho + A_2 \sin\alpha + \sum_{k+1}^{n}\left(A_{2k+1}\sin\left(\frac{2\pi k\rho}{U1}\right) + A_{2k+2}\cos\left(\frac{2\pi k\rho}{U1}\right)\right) + ET$$

Additive constant

Scale error

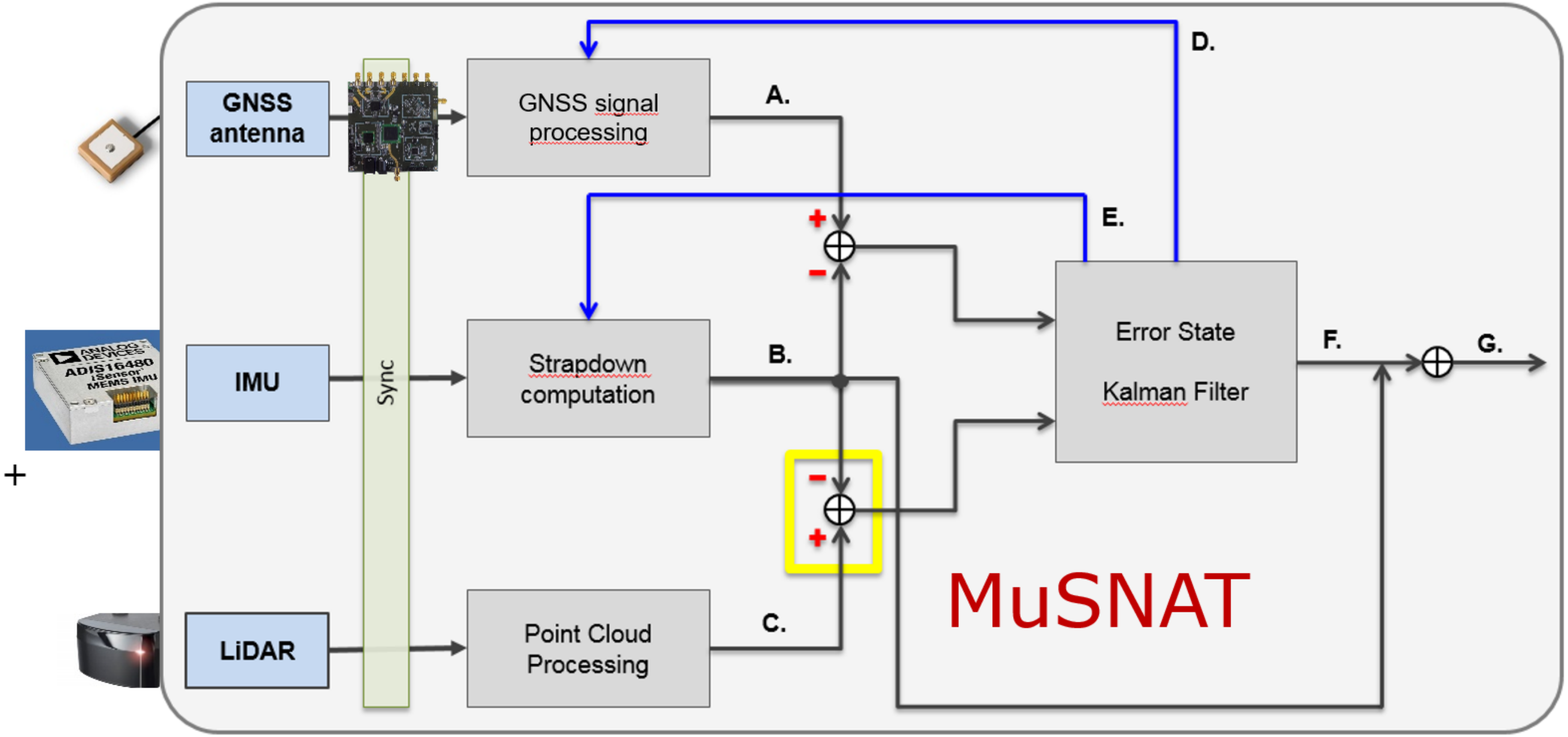
Vertical offset of the laser axis from the trunnion axis

Cyclic error terms caused by internal optical or electrical interference*

Empirical terms

* Only relevant for rangefinders that operate using the phase-difference measurement principle

Deep Sensor Fusion (GNSS, INS and LiDAR)



A. Position, code range, carrier and doppler; **B.** Position, velocity, attitude; **C.** Velocity, Dattitude**; D.** Feedback options: vector tracking, cycle slip corrections, synthetic aperture; **E.** Giro bias, acceleration

MuSNAT architecture