Linear movement with a 3D sensor

How to make a magnetic design

About this document

Scope and purpose

After reading this application note you will know how to make the magnetic design for a linear movement application with a Hall based 3D sensor. Directly, magnet and design parameters are proposed here to quickly provide a first running solution. Furthermore, some degrees of freedom or restrictions are presented. Go directly to ***Easy to use examples for "slide by"*** to check out the magnetic design proposal.

Note: *The following information is given as a hint for the implementation of our devices only and shall not be regarded as a description or warranty of a certain functionality, condition or quality of the device.*

Intended audience

This document is intended for designers to use a magnetic 3D sensor for linear position detection.

Introduction

This application note describes a possible realization of a linear movement application, e.g. for valve positions. With the new product family of the 3D Magnetic Sensor, beginning with TLV493D-A1B6, Infineon offers an innovative solution for three dimensional magnetic position sensing. By allowing a measurement of all three components of a magnetic field at the same time, it enables a multitude of applications with different ranges. Furthermore the integrated temperature sensor enables the application to compensate possible temperature-dependent magnetic field changes. The family supports automotive requirements as well, e.g. with the TLE493D-x.

Note: *Please also check out the online simulation tool at the Infineon homepage:*
https://design.infineon.com/3dsim/#/

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1 Advantages of 3D sensing

The next generation of linear movement with a 3 dimensional sensing offers many advantages:

- contactless sensing
- cost sensitive
- not sensitive to dirt
- tactile feeling can designed by mechanical interface
- higher range of motion compared to linear hall solution
- positioning between sensor and sliding interface is very flexible
- enables pass by configurations

Due to these advantages the following applications can be addressed with a magnetic 3D approach:

- valve position detection
- slider in climate controls
- volume control in mixing consoles
- collision detection in automatic cleaning robots
- ...

The state of the art solutions are by measuring the electrical resistance or detecting the position of a motor with spindle based solutions. For very high resolutions even optical or laser based systems are used. Optical systems are the most expensive solutions. For very small range of movements a one dimensional linear hall sensor can be sufficient, but this is only suitable for "Head On" configurations. A pass by configuration using 1D delivers not a unique point during the complete range of motion and is therefor not suitable for many applications.

For further information see ***Linear movement with "pass by" configuration using 1D sensor*** and ***Linear movement with "head on" configuration***.

Note: *By using 2 or 3 components of a magnetic field any movement can be detected as long as the field is higher than the noise.*

The temperature is not relevant at this approach because we do only consider relative components of the magnetic field.

2 Basic magnetic principles for linear movement

A linear movement can be detected either by "pass by" or "head on" method. The next two chapters describe the different approaches.

Definition of axis

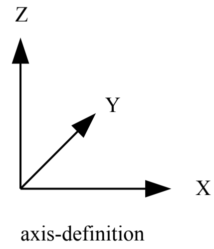

Figure 1

2.1 Linear movement with "head on" configuration

1D sensor (z-component only)

For the "head on" configuration only the B-field of the z-axis comes into effect. As the field drops very quickly via distance only small travel distances can be realized. The temperature influence must be canceled out by the microcontroller in order to get a proper position detection.

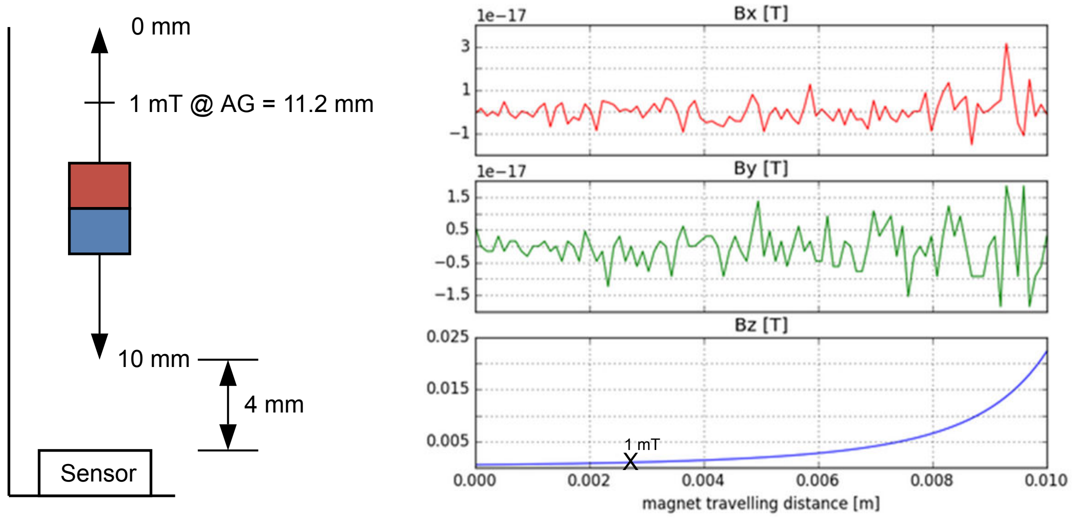

Figure 2

Table 1 Parameters

Magnetic remanenz	B_R	1400mT (rare earth magnet)
Outer diameter	Ø	2mm
Height	*h*	2mm
Air gap	*AG*	4mm .. 14mm

Conclusion

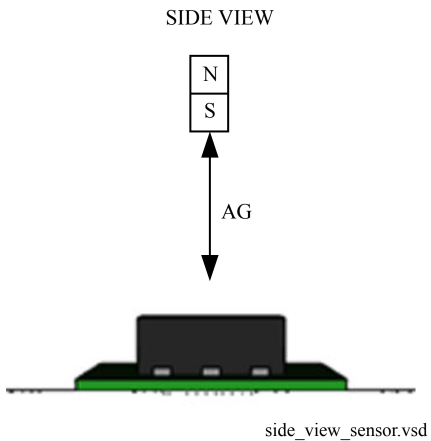

Figure 3 Magnetic field components for "head on" movement

- The sensor needs to cover a range of <1mT to ~250mT
- The range of movement is around 10mm only
- 1mT field at AG = 11.2mm

The Head on method is generally not very good for detecting linear positions. The magnetic field declines very fast. In the example above a total range of movement of about 10..12mm can be achieved by a strong NdFeB magnet. Only with bigger magnets can a higher range of movement be achieved.

Additionally, as only the z-field component is contributing to the measurement, stray field immunity is also very poor.

2.2 Linear movement with "pass by" configuration using 1D sensor

1D sensor (x- or z-component only)

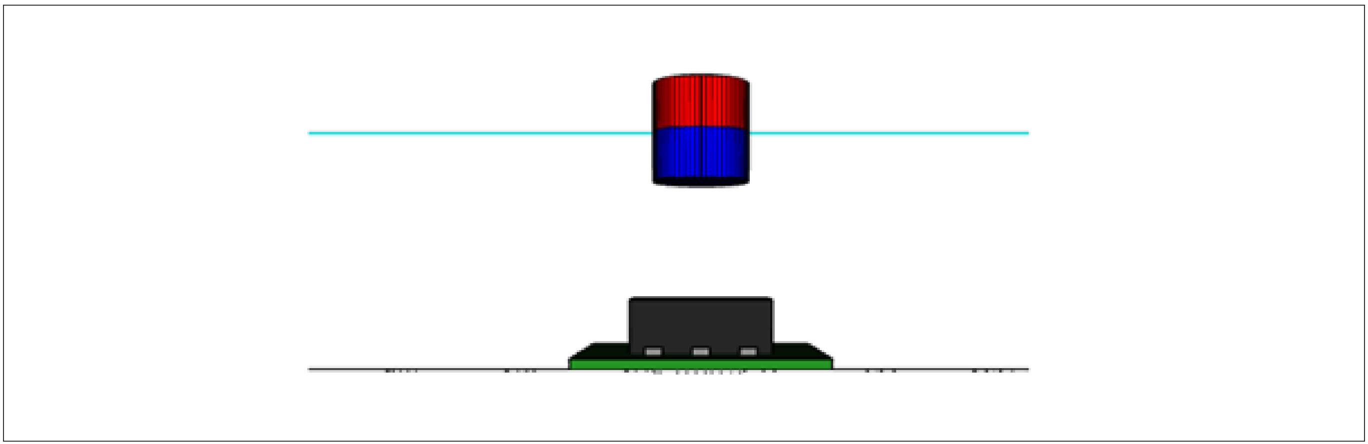

Figure 4 "Pass by" configuration

By using a 1D sensor for linear position measurement with the "pass by" you need to choose one axis of interest.

- **Using Bx**
  Bx is linear in a very small range around the center position. For using a higher range of movement the magnetic x-component is ambiguous (see ***Figure 5*** @ Bx). This means unique position detection is not possible. Only for ranges smaller than the diameter of the magnet, characterized between the min. and max. value of Bx, the detection is unique.
- **Using Bz**
  The Bz component is symmetrical around the center of movement and therefore ambiguous. If just one direction is sufficient this approach may be enough (see ***Figure 5*** @ Bz).

The temperature dependency of the magnet needs to be considered as well in both cases.

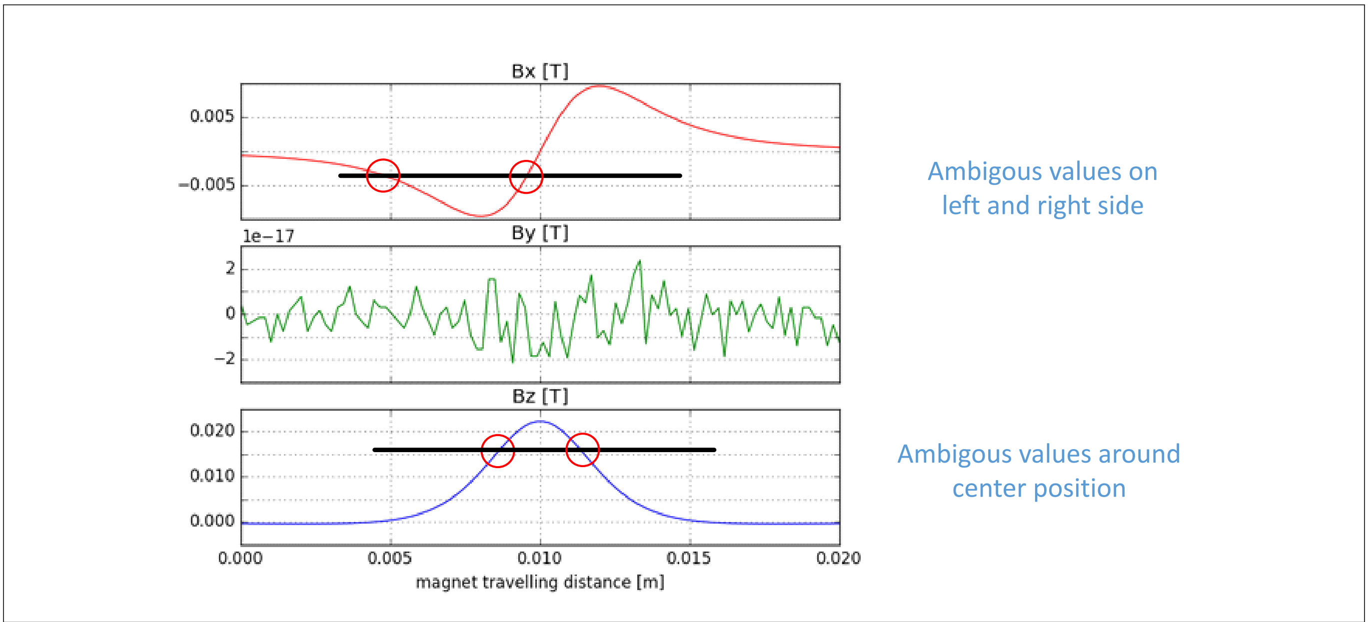

Figure 5

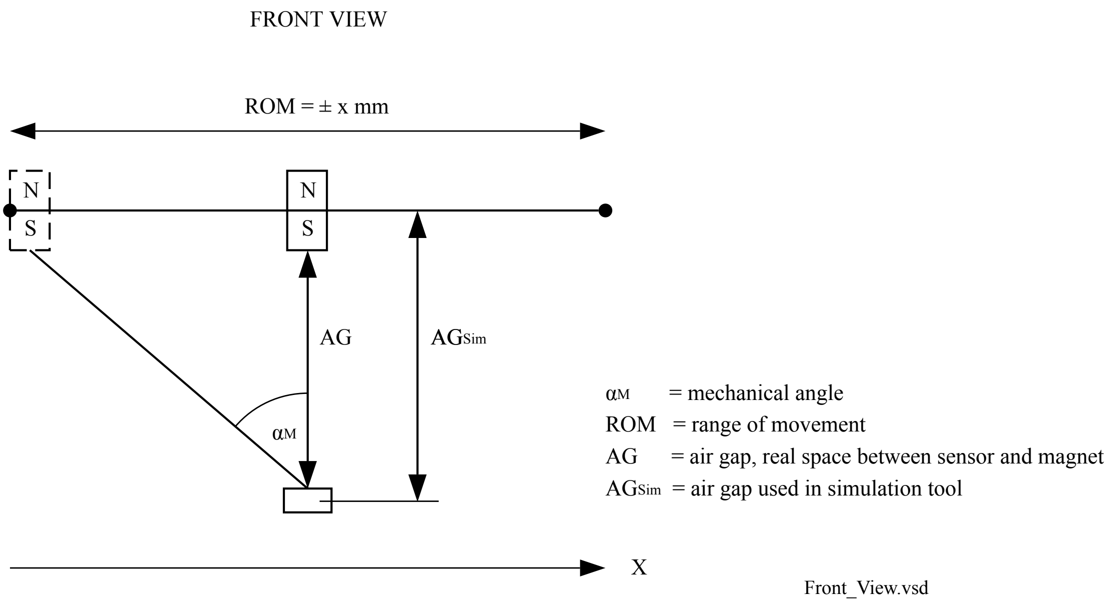

Figure 6

Table 2 Parameters for "pass by"

Magnetic remanenz	B_R	1400mT
Outer diameter	Ø	2mm
Height	*h*	2mm
Air gap (sim)[1)]	AG_{sim}	4mm
Air gap [2)]	*AG*	2.4mm

Restrictions by using a 1D sensor

- Bz is not unambiguous for both directions
- Bx is only ambiguous for each direction

→ pass by is not suitable

Conclusion

The passing by method is only suitable for sensors that can detect more than one axis. Any Sensor that can only detect the z-axis is not suitable for this application.

The 3D sensor from Infineon offers the possibility to combine the field information of more than one axis. An ATAN or ATAN2 calculation delivers the desired position. In order to get a good linearisation a factor k is introduced (see ***Figure 8*** and ***Figure 9***). See also chapter ***Differences in ATAN and ATAN2 calculation***.

1 Air gap used in simulation tool
2 Real space between sensor and magnet

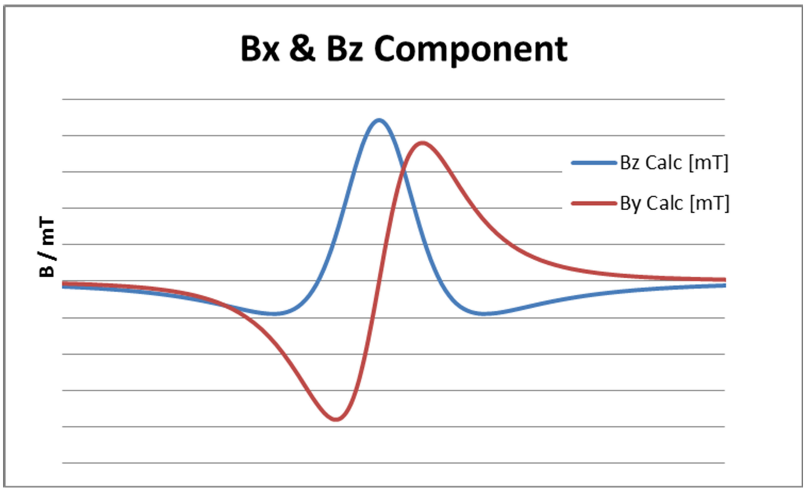

Figure 7

ATAN

By using ATAN the following graph in *Figure 8* is created. The k-factor can modulate the shape of the ATAN function.

Unfortunately the ATAN function does repeat.

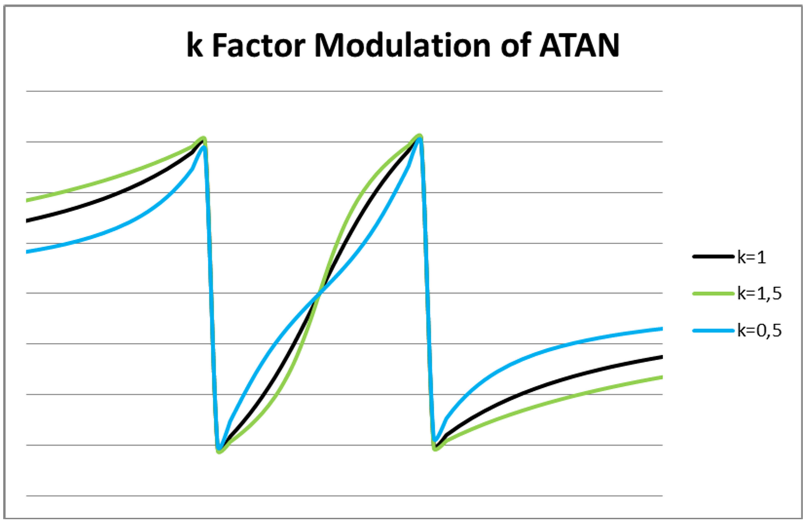

Figure 8 ATAN function and its k-factor modulation repeats periodically

$$\text{ATAN} = k \cdot \frac{\text{Bx}}{\text{Bz}}$$

ATAN2

By using ATAN2 the following graph in *Figure 9* is created. As well here the k-factor can modulate the shape of the graph. The ATAN2 function does not repeat.

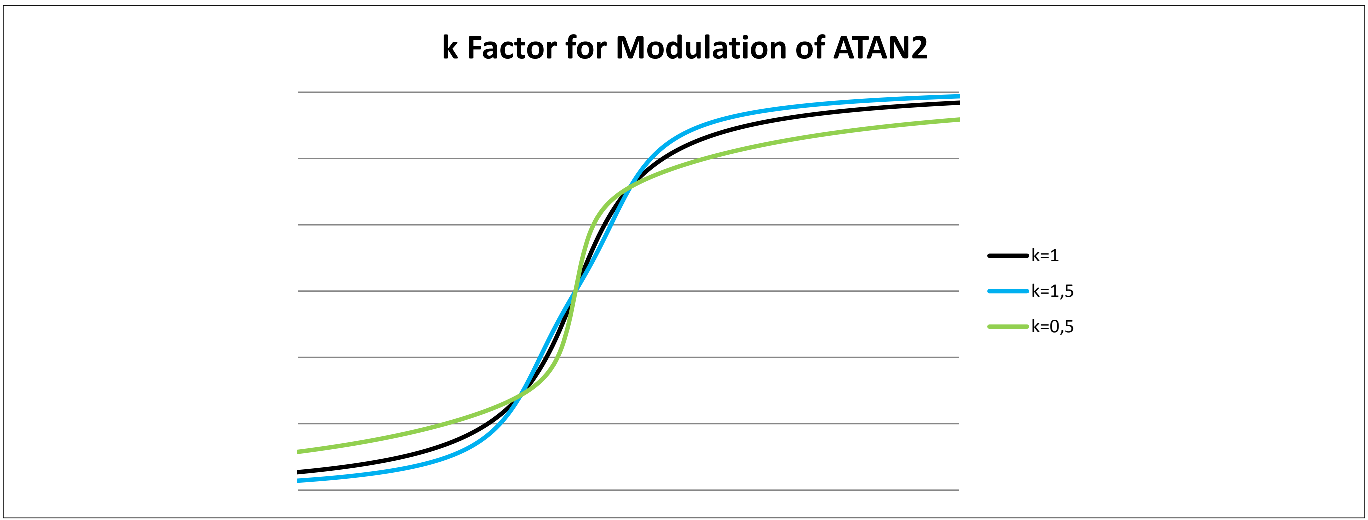

Figure 9 ATAN2 function and its k-factor modulation

$$\text{ATAN2} = k \cdot \frac{\text{Bz}}{\text{Bx}}$$

3 Simulation results

3.1 Easy to use examples for "slide by"

Following are two examples for an direct implementation.

Note: *The solutions are purely created by simulation. Any sensor errors are not considered.*

3.2 Solution 1: Cost-effective and High precision 20mm range

Solution 1 provides a cost-effective and very precise possibility for a 20mm linear position detection.

Table 3 Parameters

Magnet		***FE-S-05-05 (Y35, Ferrite)***
Magnetic remanenz	B_R	390mT
Outer diameter	Ø	10mm
Height	*h*	5mm
Air gap (sim) [1)]	AG_{sim}	10mm
Air gap [2)]	*AG*	6.85mm
Dejustage in y	*Dy*	0mm
Magnetization		axial
Range of movement	*ROM*	±10mm
Error	d_{Err}	**0.06mm**

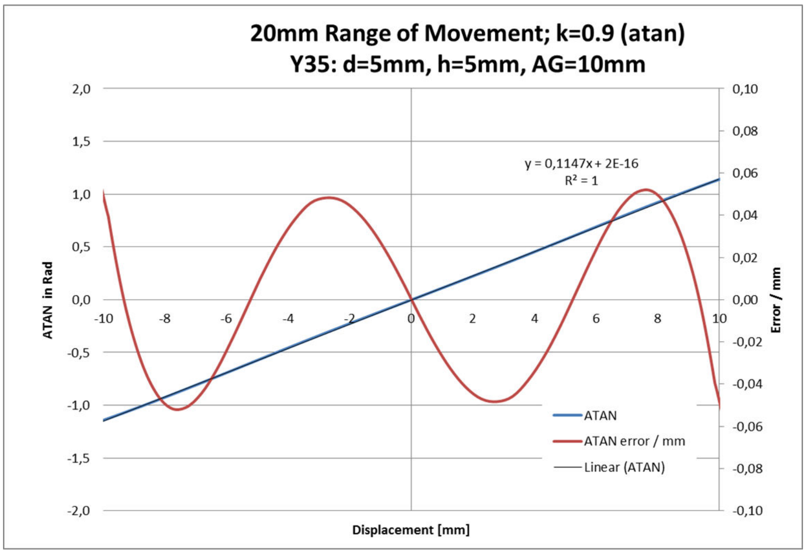

Figure 10

1 Air gap used in simulation tool
2 Real space between sensor and magnet

3.3 Solution 2: 50mm High range solution

Solution 2 provides a cost-effective possibility for a 50mm range, still with a small error.

Table 4 Parameters

Magnet		***S-05-05-N (N45, NdFeB)***
Magnetic remanenz	B_R	1020mT
Outer diameter	Ø	5mm
Height	*h*	5mm
Air gap (sim) [3]	AG_{sim}	10mm
Air gap [4]	*AG*	6.85mm
Dejustage in y	*Dy*	0mm
Magnetization		axial
Range of movement	*ROM*	±25mm
Error	d_{Err}	**<1.7mm**

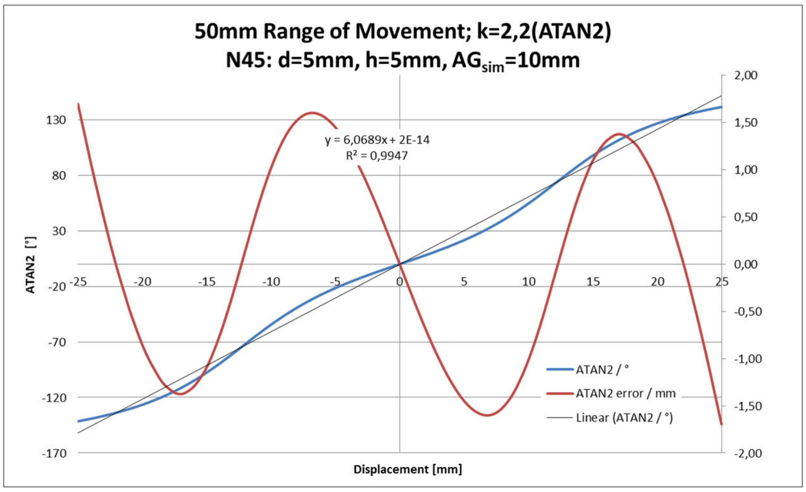

Figure 11

3 Air gap used in simulation tool
4 Real space between sensor and magnet

3.4 Overview

Overview of further solutions

This chapter will give you more details about the solution 1 (in table ***0.06***) and solution 2 (in table ***1.7***). Furthermore other ranges, parameters and the corresponding errors will be indicated.

Table 5 Overview of errors

Magnet					Range of movement and position errors in mm						Link to simulation details
	BR	**d**	**h**	**AG_{sim}[5)]**	**10**	**15**	**20**	**30**	**40**	**50**	
Y35	390mT	5mm	5mm	10mm	0.005[6)]	0.04[6)]	**0.06**[6)7)]	1.1	1.2	2	***Chapter 3.4.1***
N45	1020mT	5mm	5mm	10mm	0.004[6)]	-	0.04[6)]	0.2[8)]	0.6	**1.7**[9)]	***Chapter 3.4.2***
Y35	390mT	10mm	5mm	5mm	0.03[6)]	0.2	0.4	1.4	3.3	-	***Chapter 3.4.3***
N35	390mT	5mm	5mm	5mm	0.1[6)]	0.2	0.4[6)]	2	4	6	***Chapter 3.4.4***
N45	1020mT	10mm	5mm	5mm	0.03[6)]	0.2	0.4	1.4	3.3	5	***Chapter 3.4.5***
N45	1020mT	5mm	5mm	5mm	0.1[6)]	0.2	0.4[6)]	2	4	6	***Chapter 3.4.6***
N45	1020mT	5mm	5mm	8mm	0.02[6)]	0.03[6)]	0.1[6)]	0.5[10)]	1.6	3.7	***Chapter 3.4.7***
Y35	390mT	5mm	5mm	8mm	0.01[6)]	0.05[6)]	0.15	0.4	1.3	3	***Chapter 3.4.8***

Conclusion

1. The bigger the diameter of the magnet the more precise is the position detection at a certain airgap.
2. An increase of the magnetic field strength at same geometry will <u>not increase</u> the precision, but will increase the robustness to stray fields.
3. An increase of the field may be needed in order to get enough magnetic field at the end of the motion.
4. An increase in air gap leads to higher precision.

5 AGsim = AG + h/2 + 0.65mm (h: height of the magnet)
6 ATAN calculation
7 **Solution 1**
8 0.1mm for 26mm range of movements, calculated with ATAN
9 **Solution 2**
10 0.2mm for 28mm range of movements, calculated with ATAN

3.4.1 Simulation 1: Y35, d = 5mm, h = 5mm, AG_{sim} = 10mm

Y35 - Magnetized Magnet, d = 5mm, h = 5mm, AG_{sim} = 10mm (Solution 1)
For other simulations see also ***Overview of further solutions***.

Table 6 Parameters

Magnet		Y35
Magnetic remanenz	B_R	390mT
Outer diameter	Ø	5mm
Height	*h*	5mm
Air gap (sim)	AG_{sim}	10mm
Air gap	*AG*	6.75mm
Dejustage in y	*Dy*	0mm
Magnetization		axial
Range of movement	*ROM*	±5mm to ±25mm
Error	d_{Err}	±0.005mm to ±2mm

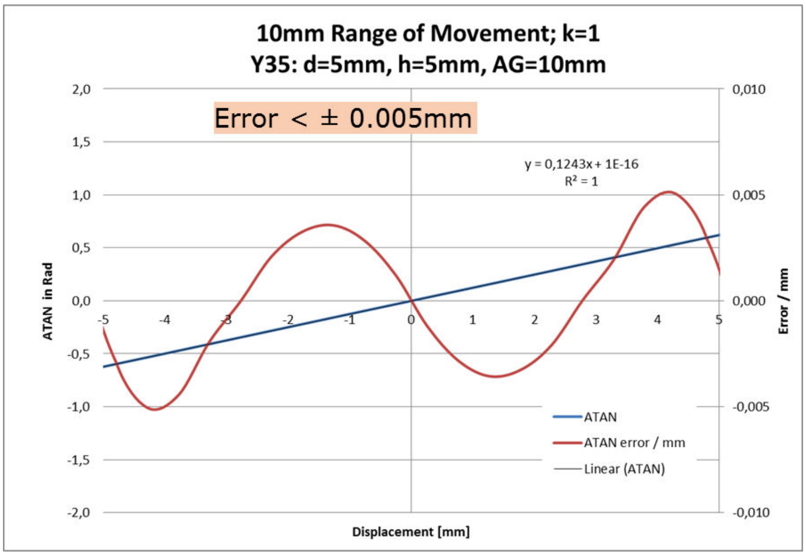

Figure 12

3 Simulation results

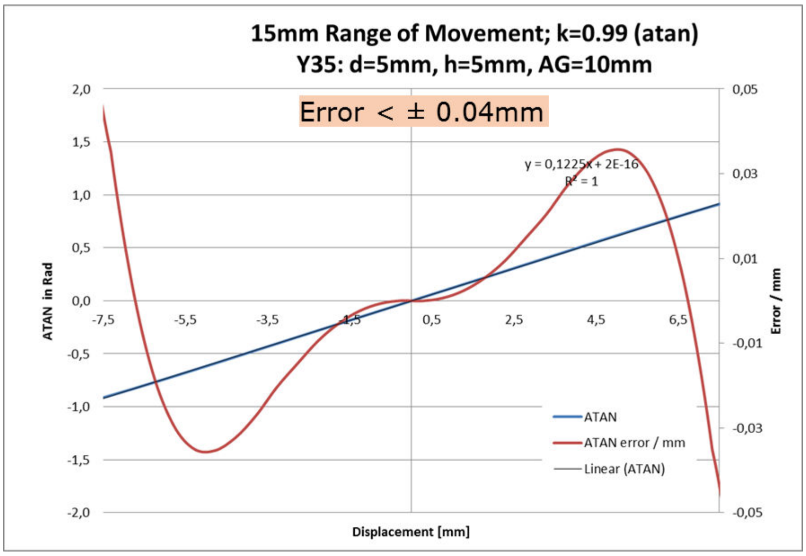

Figure 13

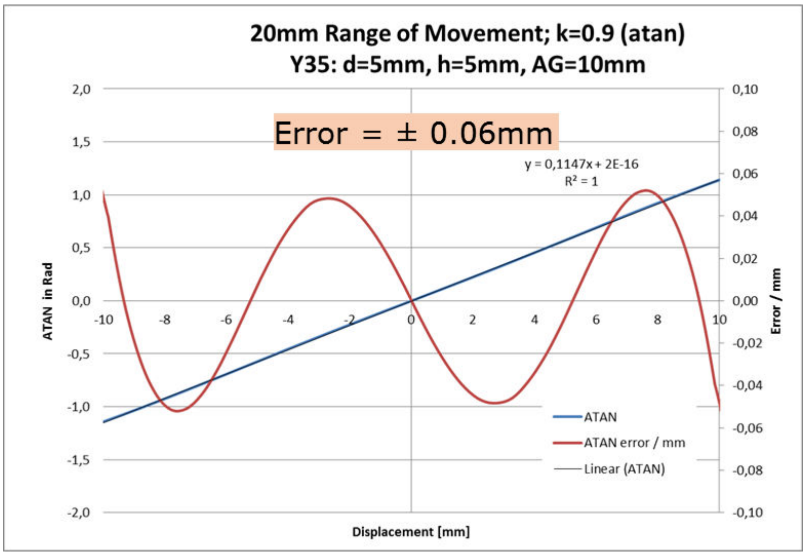

Figure 14 Solution 1

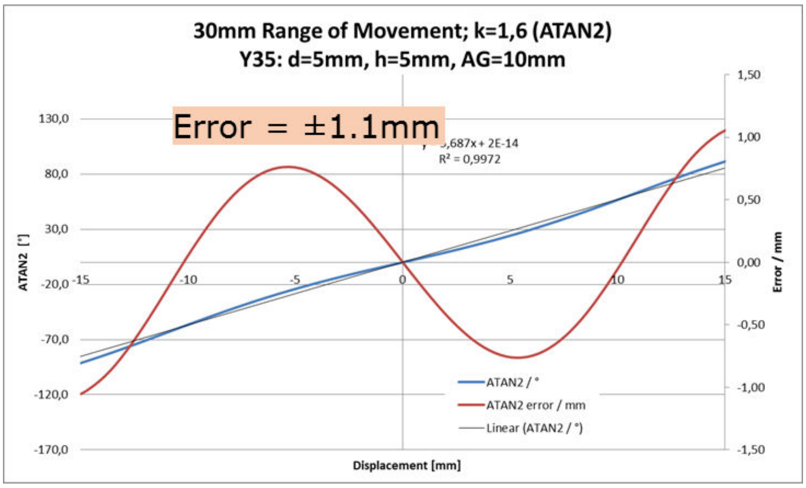

Figure 15

3 Simulation results

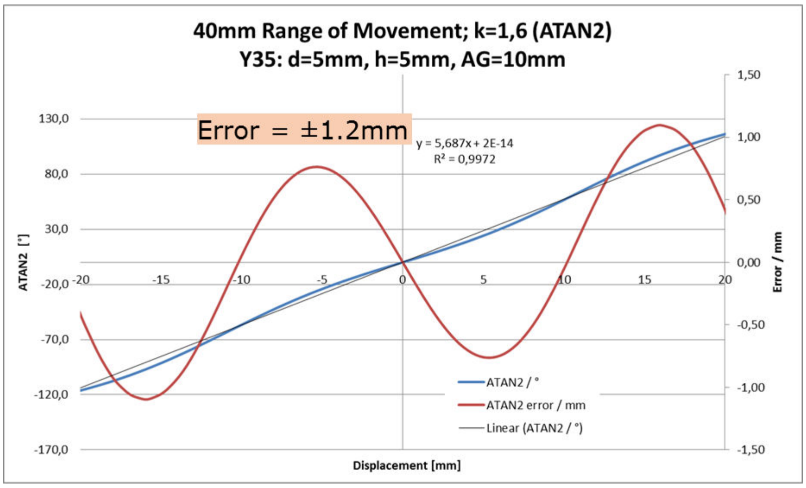

Figure 16

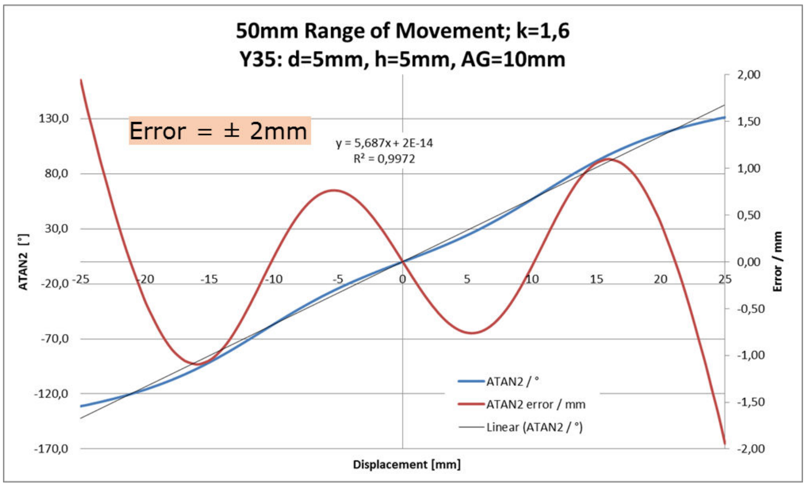

Figure 17

3.4.2 Simulation 2: N45, d = 5mm, h = 5mm, AG_{sim} = 10mm

N45 - Magnetized Magnet, d = 5mm, h = 5mm, AG_{sim} = 10mm (Solution 2)
For other simulations see also ***Overview of further solutions***.

Table 7 Parameters

Magnet		N45
Magnetic remanenz	B_R	1020mT
Outer diameter	Ø	5mm
Height	h	5mm
Air gap (sim)	AG_{sim}	10mm
Air gap	AG	6.75mm
Dejustage in y	Dy	0mm
Magnetization		axial
Range of movement	ROM	±5mm to ±25mm
Error	d_{Err}	±0.004mm to ±1.7mm

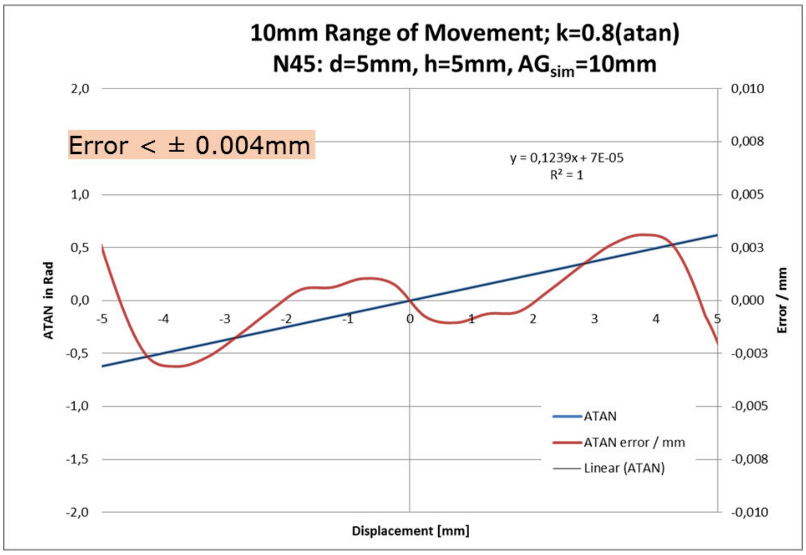

Figure 18

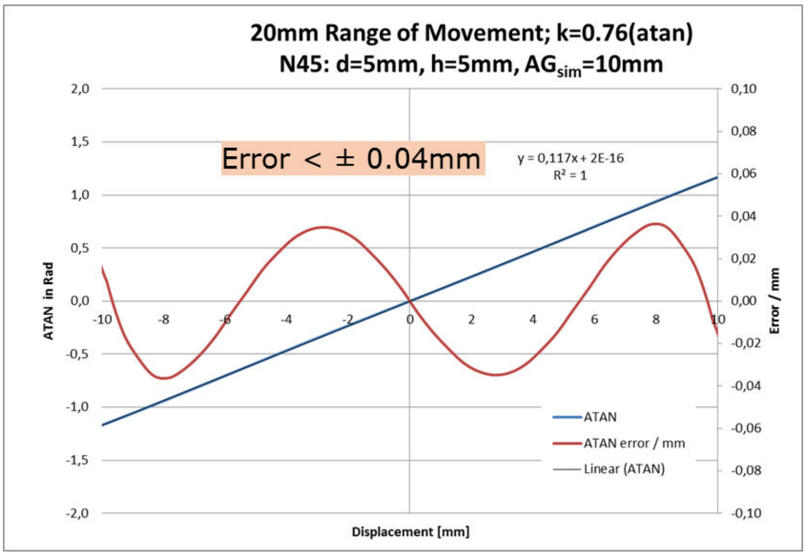

Figure 19

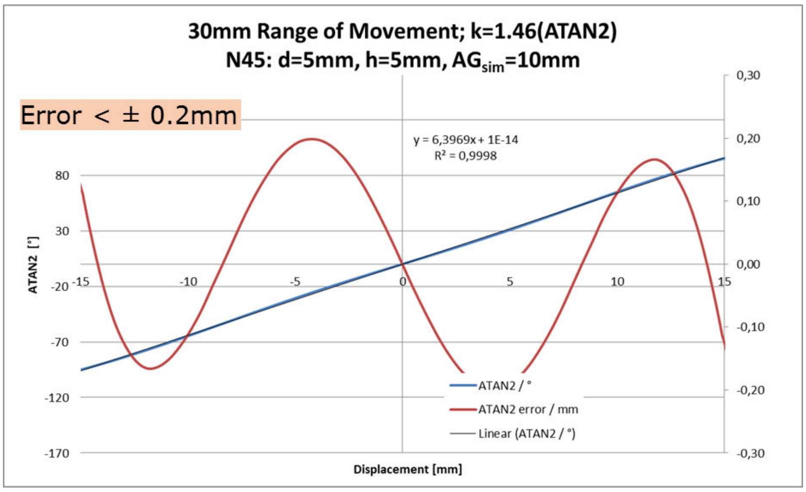

Figure 20

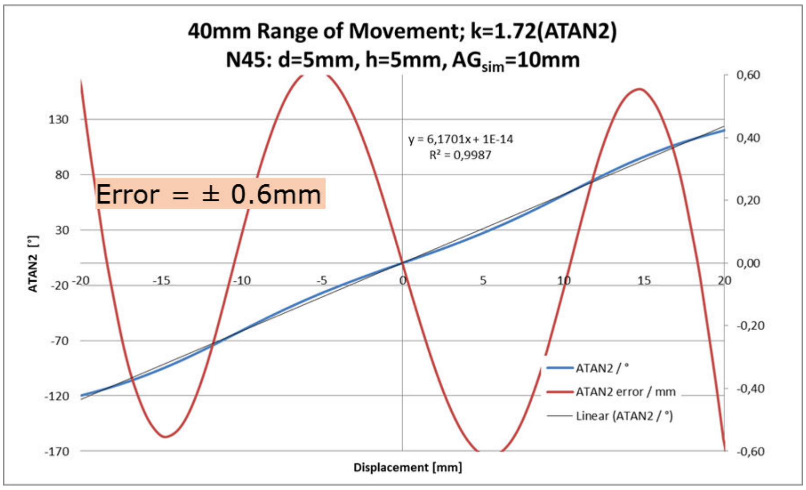

Figure 21

3 Simulation results

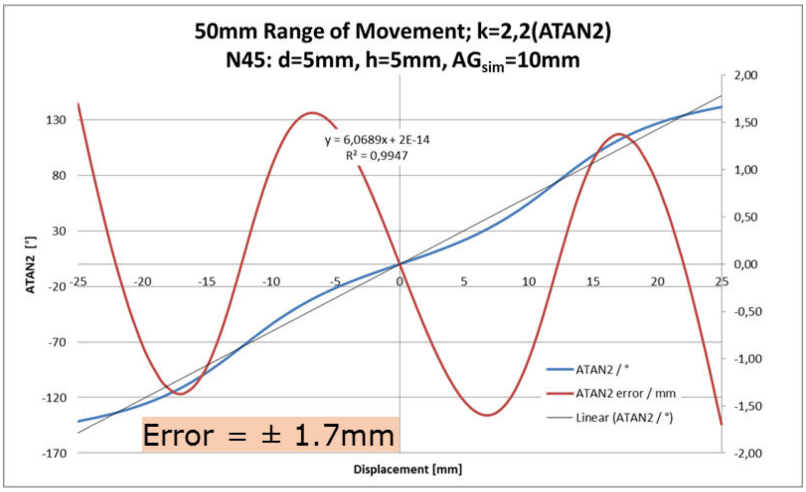

Figure 22 Solution 2

3.4.3 Simulation 3: Y35, d = 10mm, h = 5mm, AG_{sim} = 5mm

Y35 - Magnetized Magnet, d = 10mm, h = 5mm, AG_{sim} = 5mm

For other simulations see also ***Overview of further solutions***.

Table 8 Parameters

Magnet		Y35
Magnetic remanenz	B_R	390mT
Outer diameter	Ø	10mm
Height	*h*	5mm
Air gap (sim)	AG_{sim}	5mm
Air gap	*AG*	1.85mm
Dejustage in y	*Dy*	0mm
Magnetization		axial
Range of movement	*ROM*	±5mm to ±20mm
Error	d_{Err}	±0.05mm to ±3mm

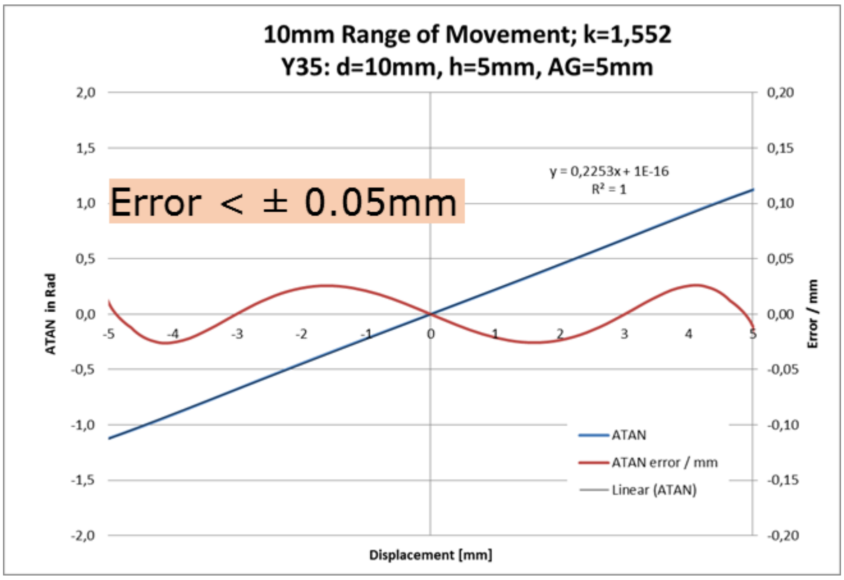

Figure 23

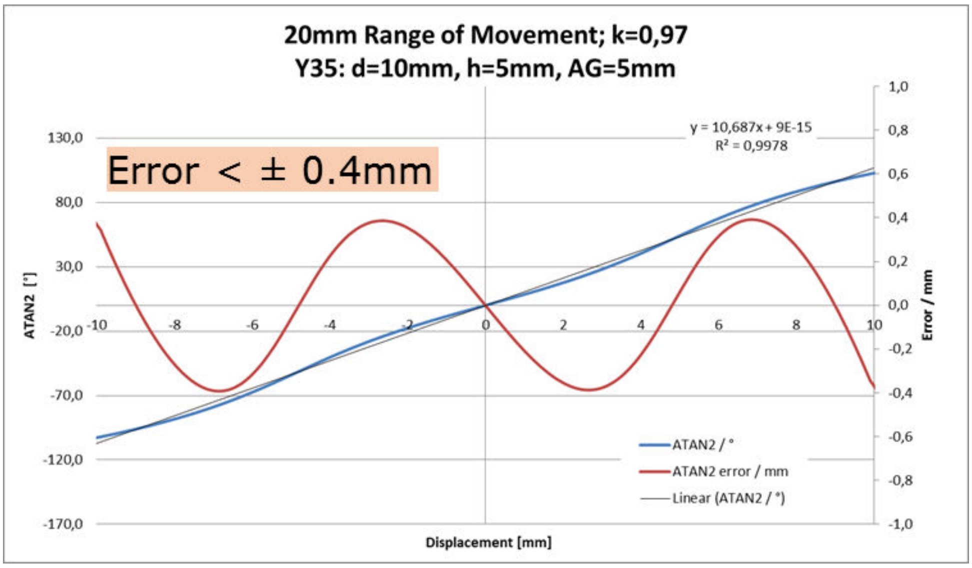

Figure 24

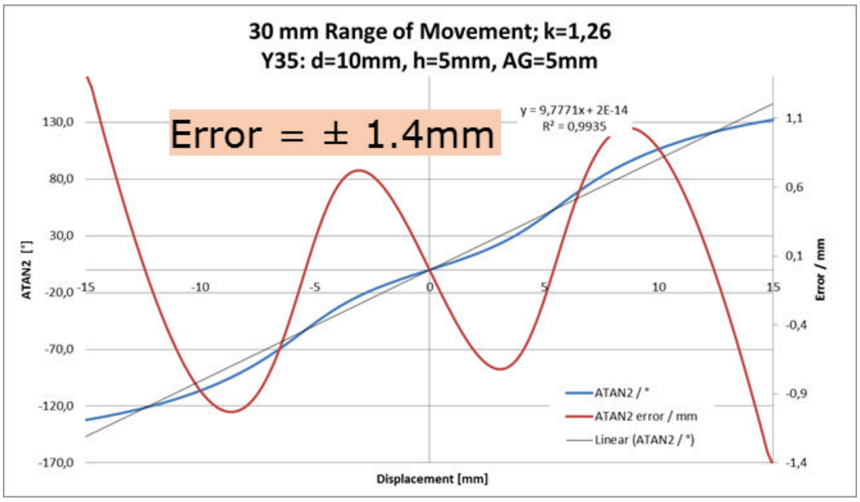

Figure 25

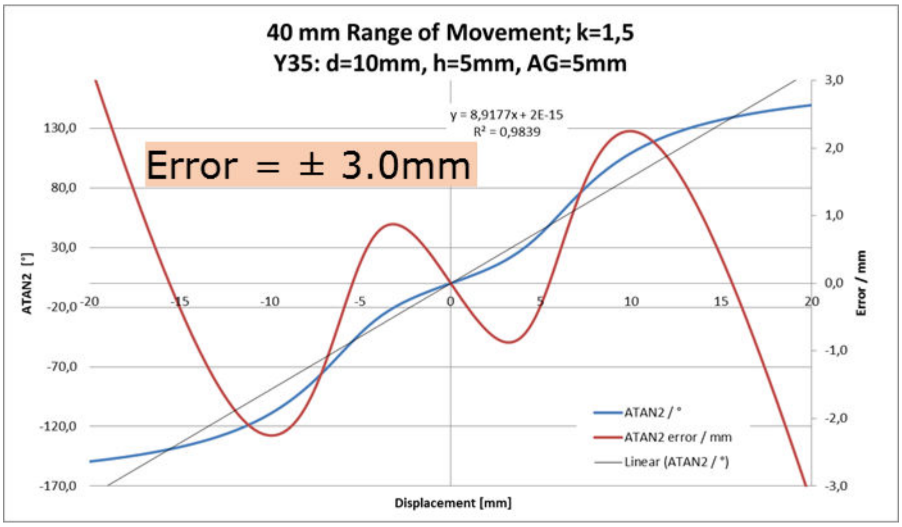

Figure 26

3.4.4 Simulation 4: Y35, d = 5mm, h = 5mm, AG_{sim} = 5mm

Y35 - Magnetized Magnet, d = 5mm, h = 5mm, AG_{sim} = 5mm
For other simulations see also ***Overview of further solutions***.

Table 9 Parameters

Magnet		Y35
Magnetic remanenz	B_R	390mT
Outer diameter	Ø	5mm
Height	*h*	5mm
Air gap (sim)	AG_{sim}	5mm
Air gap	*AG*	1.85mm
Dejustage in y	*Dy*	0mm
Magnetization		axial
Range of movement	*ROM*	±5mm to ±25mm
Error	d_{Err}	±0.1mm to ±6.0mm

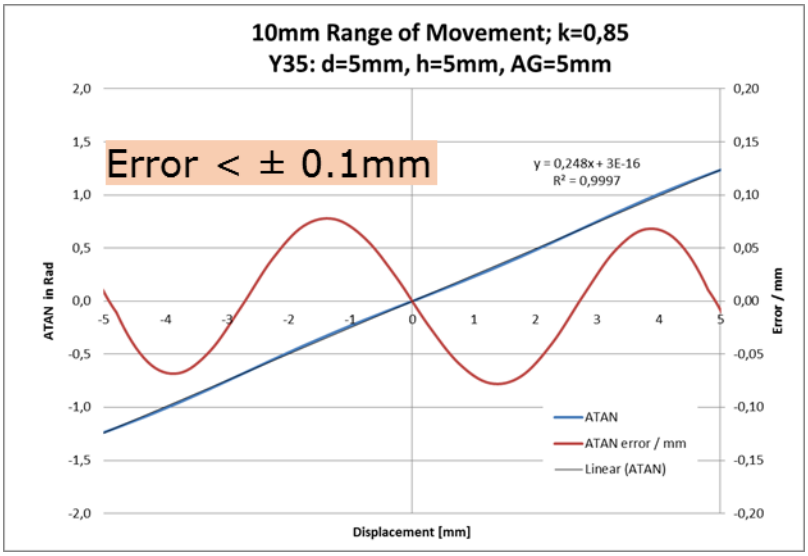

Figure 27

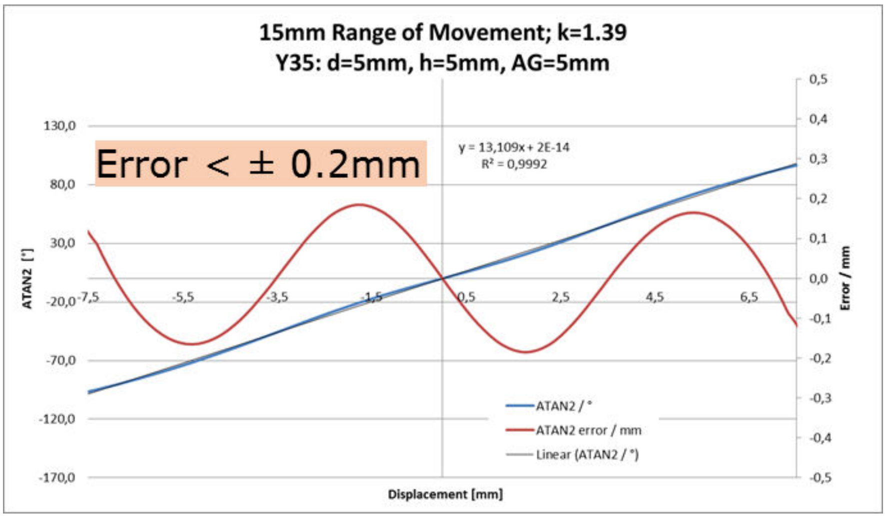

Figure 28

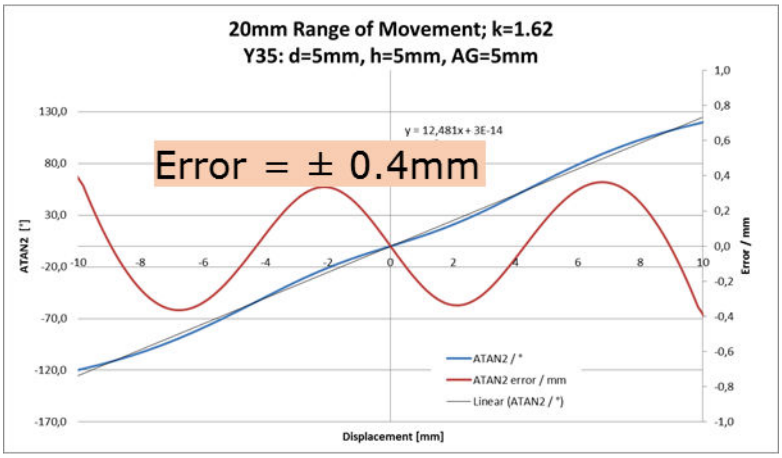

Figure 29

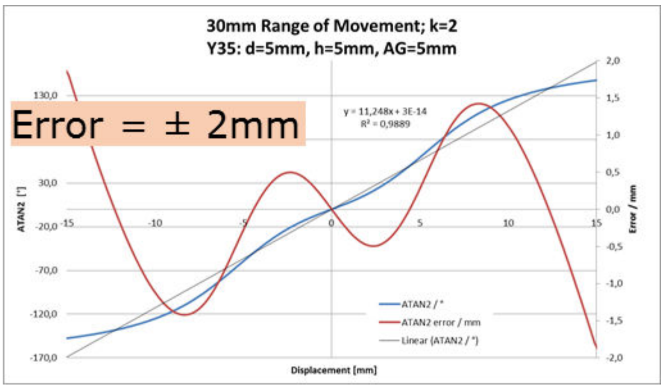

Figure 30

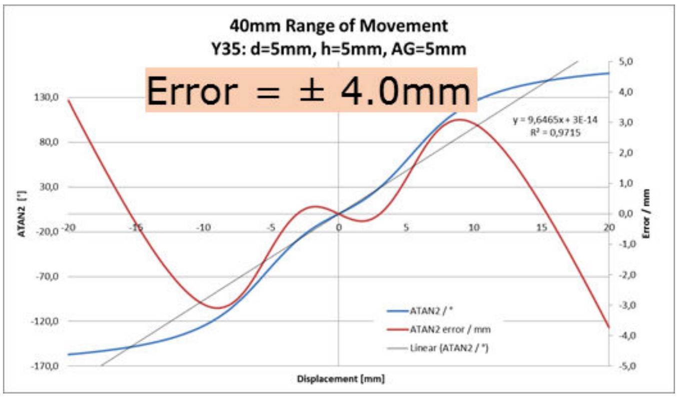

Figure 31

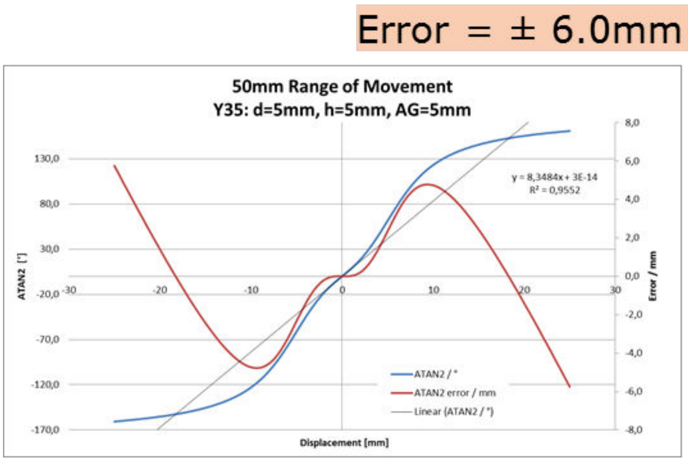

Figure 32

3.4.5 Simulation 5: N45, d = 10mm, h = 5mm, AG_{sim} = 5mm

N45 - Magnetized Magnet, d = 10mm, h = 5mm, AG_{sim} = 5mm

For other simulations see also ***Overview of further solutions***.

Table 10 Parameters

Magnet		N45
Magnetic remanenz	B_R	1020mT
Outer diameter	Ø	10mm
Height	h	5mm
Air gap (sim)	AG_{sim}	5mm
Air gap	AG	1.85mm
Dejustage in y	Dy	0mm
Magnetization		axial
Range of movement	ROM	±5mm to ±25mm
Error	d_{Err}	±0.03mm to ±5mm

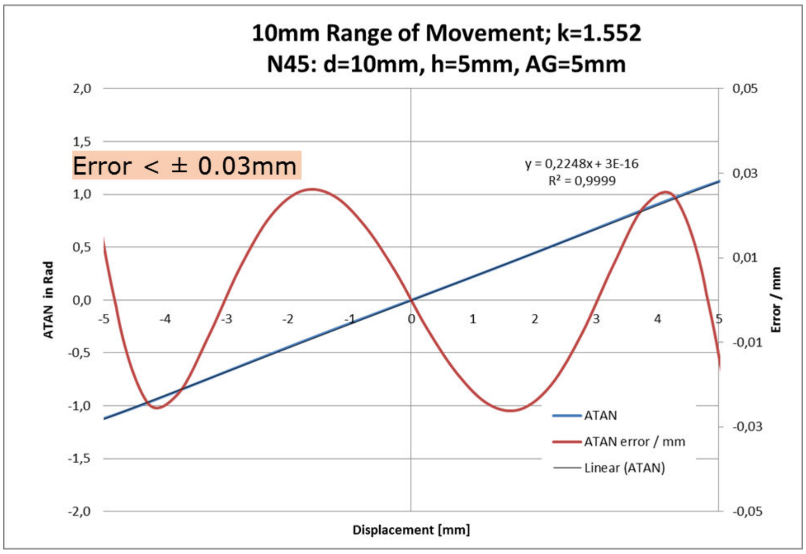

Figure 33

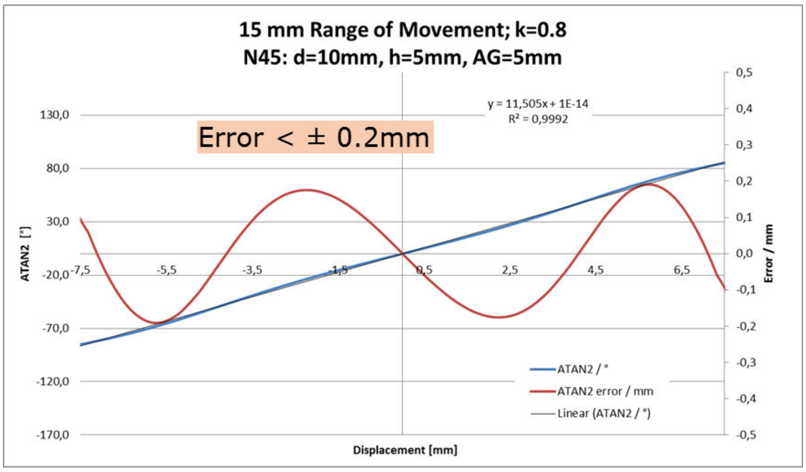

Figure 34

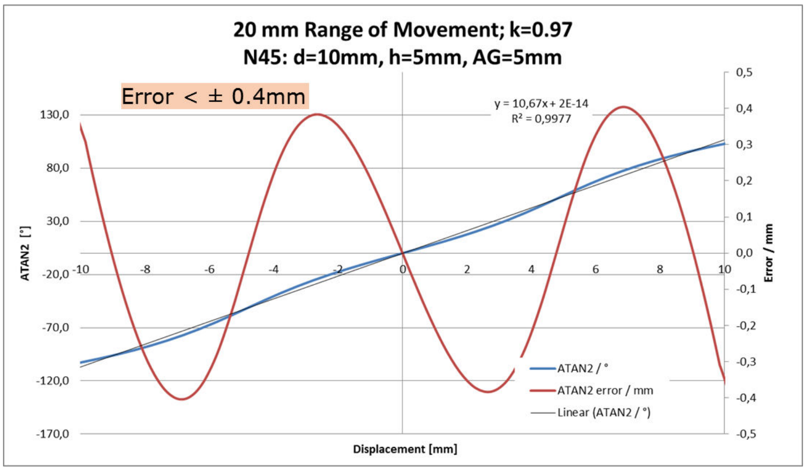

Figure 35

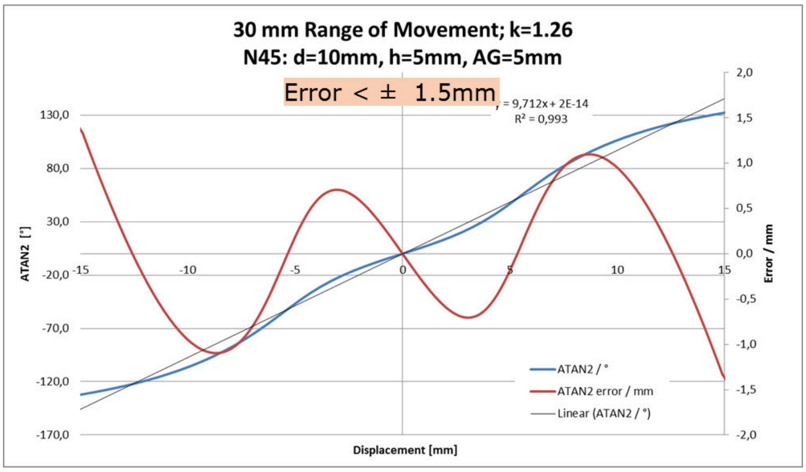

Figure 36

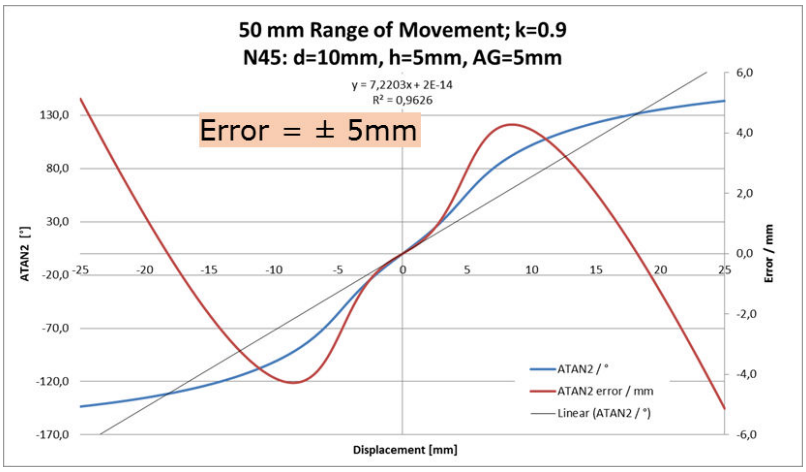
50 mm Range of Movement; k=0.9
N45: d=10mm, h=5mm, AG=5mm
y = 7,2203x + 2E-14
R² = 0,9626
Error = ± 5mm
ATAN2 [°]
Error / mm
Displacement [mm]
ATAN2 / °
ATAN2 error / mm
Linear (ATAN2 / °)

Figure 37

3.4.6 Simulation 6: N45, d = 5mm, h = 5mm, AG_{sim} = 5mm

N45 - Magnetized Magnet, d = 5mm, h = 5mm, AG_{sim} = 5mm

For other simulations see also ***Overview of further solutions***.

Table 11 Parameters

Magnet		N45
Magnetic remanenz	B_R	1020mT
Outer diameter	Ø	5mm
Height	h	5mm
Air gap (sim)	AG_{sim}	5mm
Air gap	AG	1.85mm
Dejustage in y	Dy	0mm
Magnetization		axial
Range of movement	ROM	±5mm to ±25mm
Error	d_{Err}	±0.1mm to ±6mm

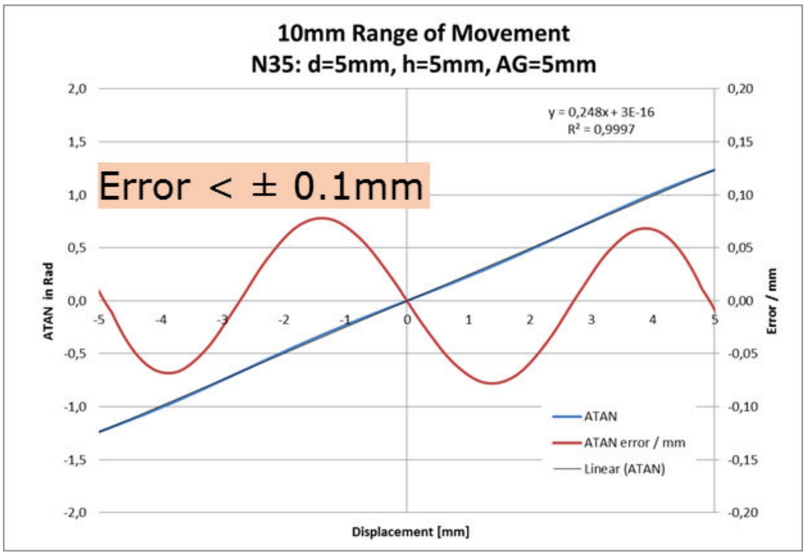

Figure 38

3 Simulation results

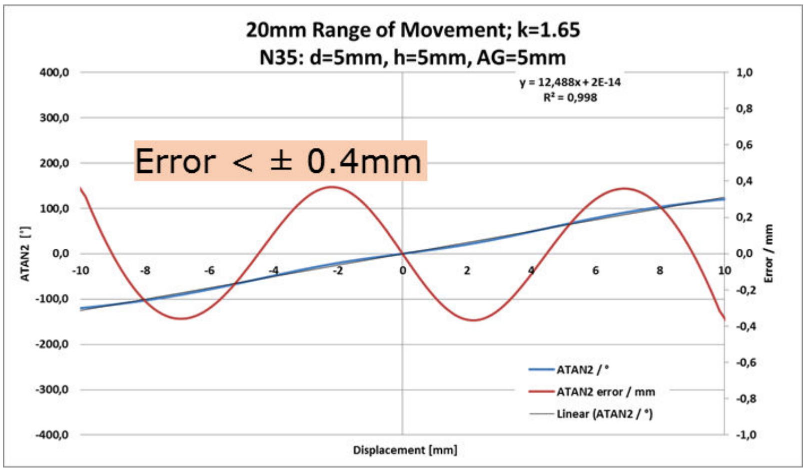

Figure 39

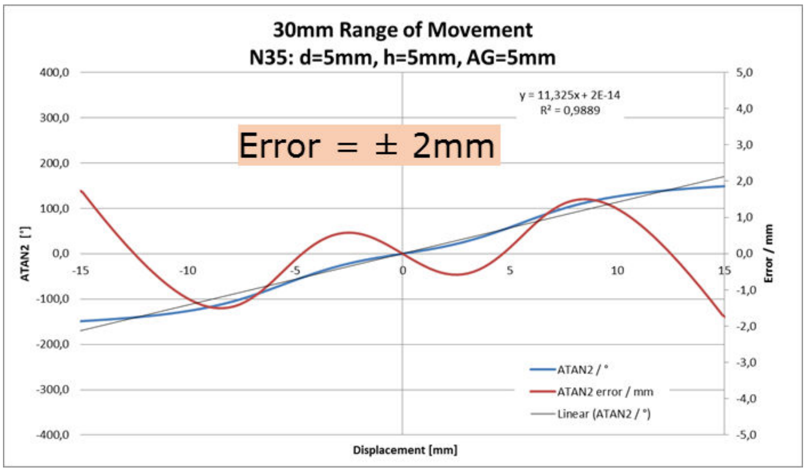

Figure 40

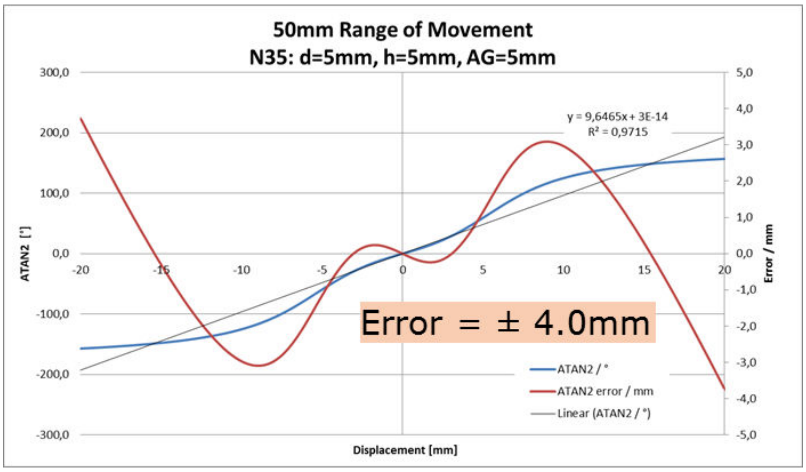

Figure 41

3 Simulation results

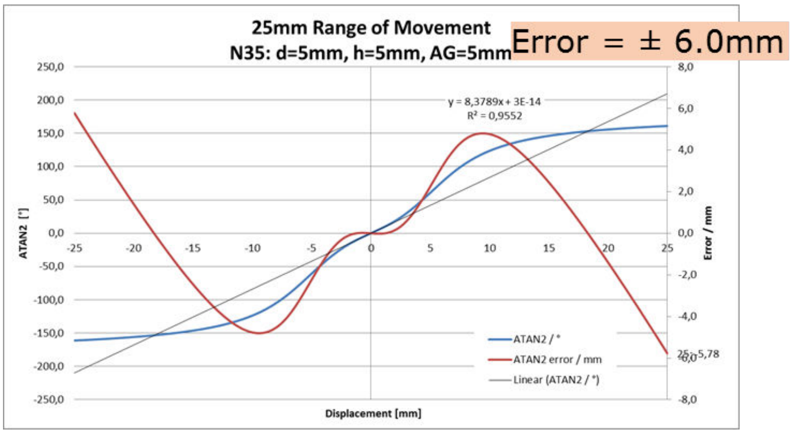

Figure 42

3.4.7 Simulation 7: N45, d = 5mm, h = 5mm, AG_{sim} = 8mm

N45 - Magnetized Magnet, d = 5mm, h = 5mm, AG_{sim} = 8mm

For other simulations see also ***Overview of further solutions***.

Table 12 Parameters

Magnet		N45
Magnetic remanenz	B_R	1020mT
Outer diameter	Ø	5mm
Height	*h*	5mm
Air gap (sim)	AG_{sim}	8mm
Air gap	*AG*	4.85mm
Dejustage in y	*Dy*	0mm
Magnetization		axial
Range of movement	*ROM*	±5mm to ±25mm
Error	d_{Err}	±0.03mm to ±3.7mm

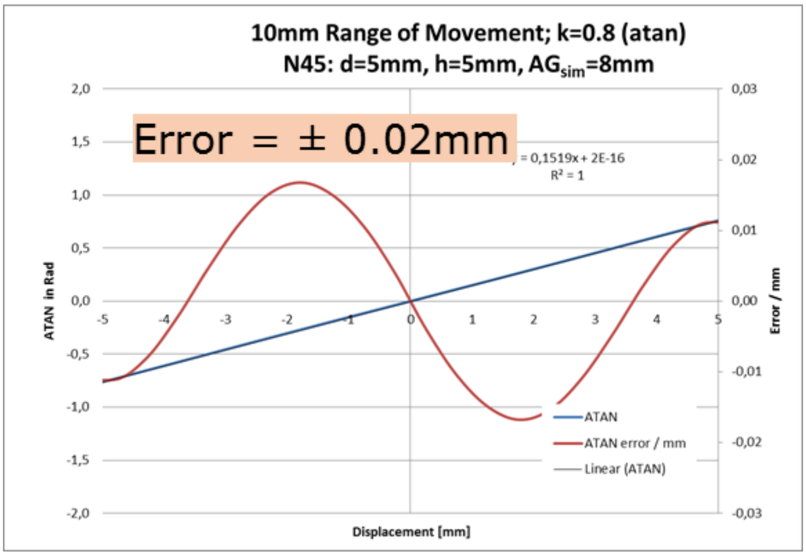

Figure 43

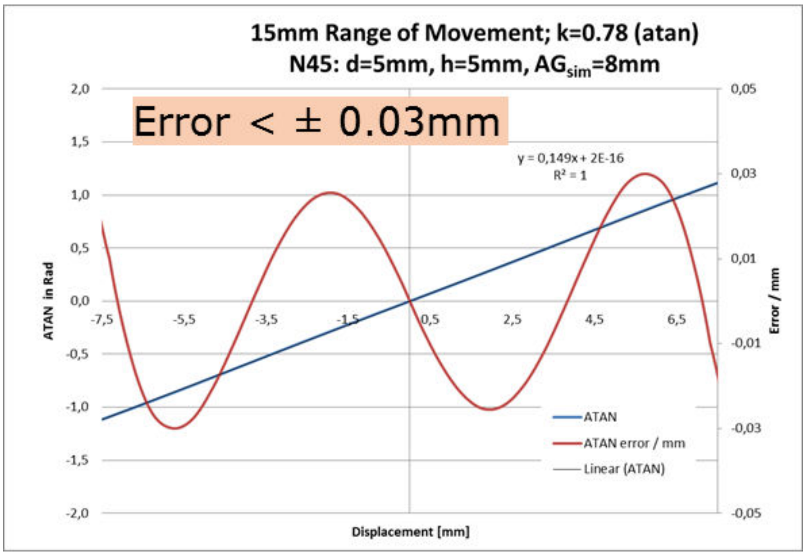

Figure 44

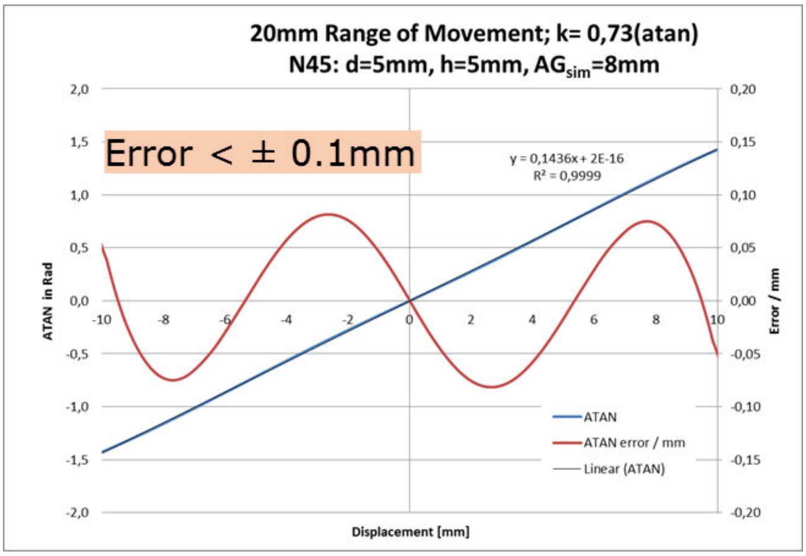

Figure 45

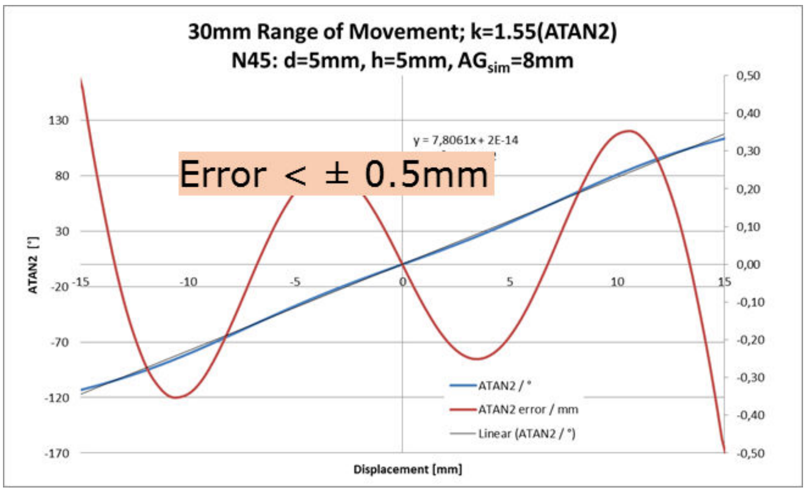

Figure 46

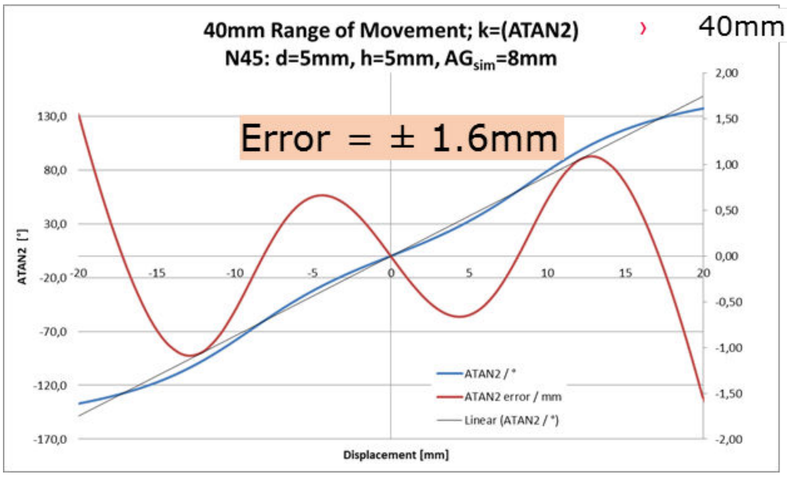

Figure 47

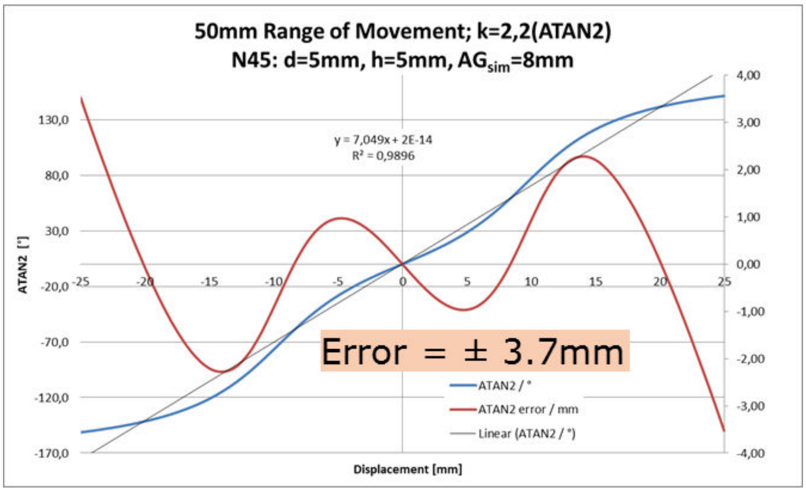

Figure 48

3.4.8 Simulation 8: Y35 , d = 5mm, h = 5mm, AG_{sim} = 8mm

Y35 - Magnetized Magnet, d = 5mm, h = 5mm, AG_{sim} = 8mm

For other simulations see also ***Overview of further solutions***.

Table 13 Parameters

Magnet		Y35
Magnetic remanenz	B_R	390mT
Outer diameter	Ø	5mm
Height	*h*	5mm
Air gap (sim)	AG_{sim}	8mm
Air gap	*AG*	4.85mm
Dejustage in y	*Dy*	0mm
Magnetization		axial
Range of movement	*ROM*	±5mm to ±25mm
Error	d_{Err}	±0.01mm to ±3mm

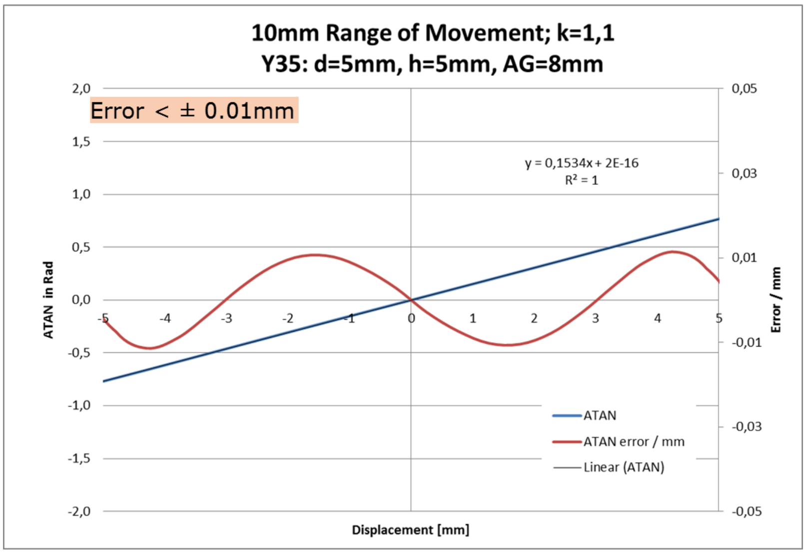

Figure 49

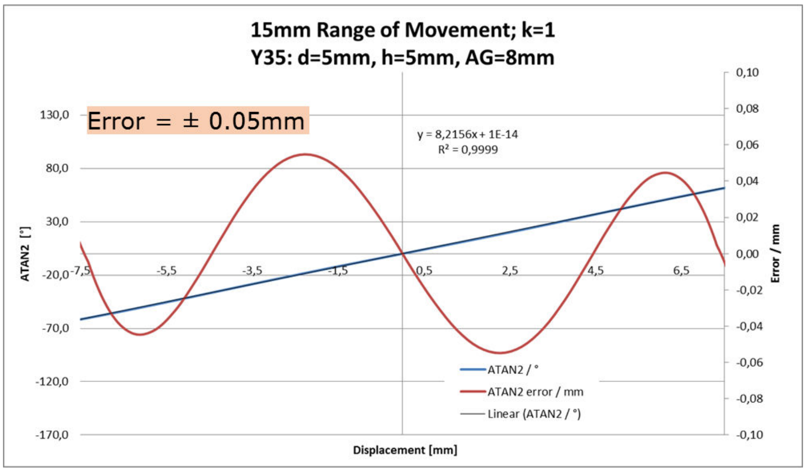

Figure 50

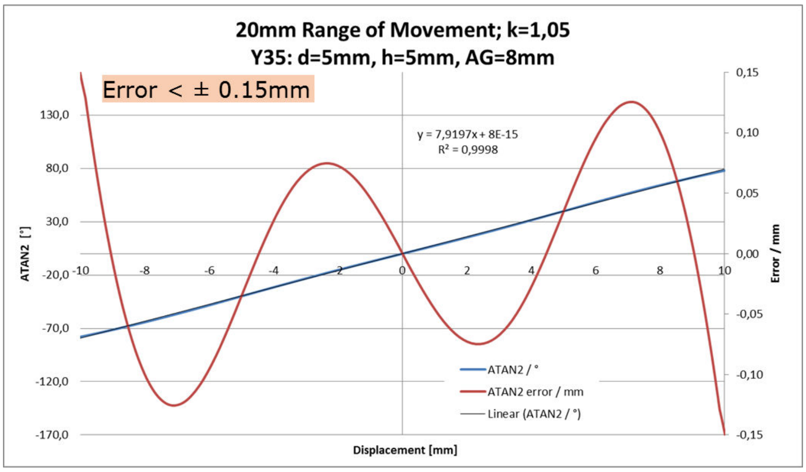

Figure 51

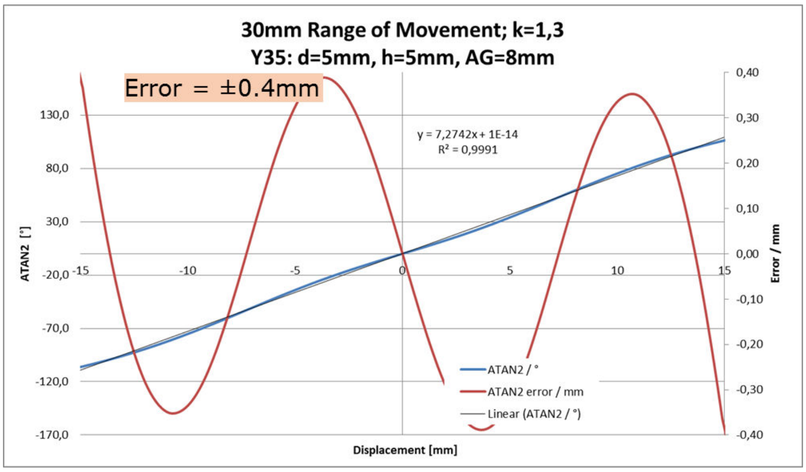

Figure 52

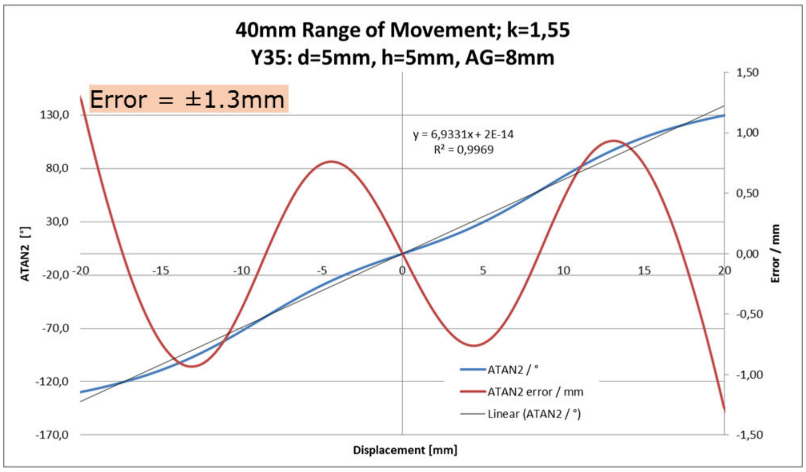

Figure 53

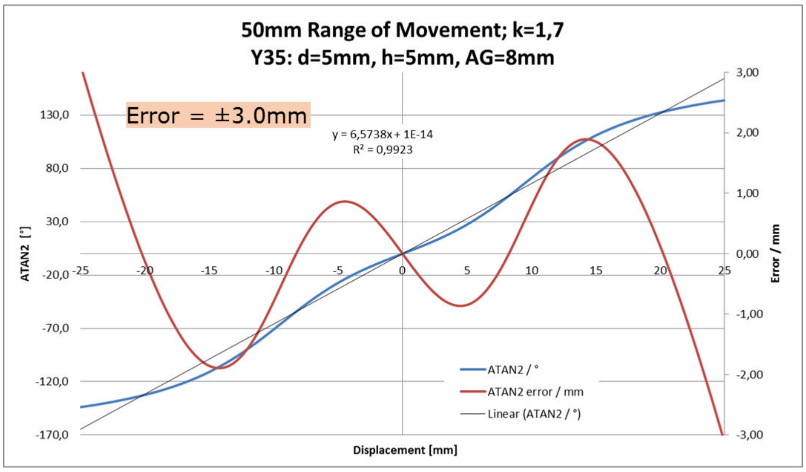

Figure 54

4 Calibration and calculation

4.1 Calibration procedure and running mode

Magnetic design

First of all, a magnetic design shall be made in order to find a proper magnetic circuit. Most important outcome shall be the linear range of the ATAN or ATAN2 calculation. If no linearisation is needed a lockup table can be used as well.

Multi-point calibration in application

1. Collect Bx, By & Bz from –x to x (Range of movement = -x .. x)
2. Calculate Offset & Gain (see ***calibration of sensor errors***)
3. Calculate ATAN or ATAN2

   ATAN for small ranges (<~7mm). ATAN2 for higher ranges (see also ***Differences in ATAN and ATAN2 calculation***)
4. Create linear trend line by using e.g. Microsoft Excel

   Vary k of the TAN or TAN2 function in order to get best fit of the linear trend line → "Slope" of the trend line
5. Safe Offset, Gain & k-factor for every device in the microcontroller

   ATAN = "Slope" × position or ATAN2 = "Slope" × position

Calibration of sensor errors

1. Offset-calibration:
   a. → Read out sensor offset @ B=0mT and store Bx, By and Bz offset calibration values
2. Gain-calibration:
   a. Apply a dedicated field in x, y and z direction and store the values
   b. Apply a dedicated 2nd field with negative sign for x, y and z direction
   c. → Calculated gain for x, y and z component and store a correction factor
3. To increase accuracy a calibration via temperature can be done in addition

Two point calibration in application

Out of the primary executed simulation the linear range of the movement is determined.

The magnetic circuit shall be modified in order to find the linear range and to meet the accuracy targets.

1. Move the magnet to the one extrema (=position 1) of the movement and measure x, (y and) z-component. Please correct offset and gain.
2. Move the magnet to the 2nd extrema (=position 2) of the movement and measure x, (y and) z-component. Please correct offset and gain.
3. Calculate ATAN or ATAN2 @ position 1 and position 2. Whether ATAN or ATAN2 shall be used depends on linear range and the accuracy you need to cover.
4. Create a linear trend line: ATAN = m × x or ATAN2 = m × x

   with m:= slope of the trend line [°/mm or rad/mm]; x:= position [mm]

Running mode

In order to get the position the Bx, By and Bz component will be measured. Please correct offset and gain. Out of the correct components the ATAN or ATAN2 is calculated.

→ Position x = ATAN / m

→ Position x = ATAN2 / m

Note: *The k-factor can be used to modulate the ATAN line as stated in **Differences in ATAN and ATAN2 calculation** to improve accuracy. An further increase of accuracy can be reached by using more points for calibration and store them in a look up table.*

4.2 No calibration

If there is no possibility or need to have a calibration upfront you could use the following idea to realize a position detection as well.

Use standard values for Bz, Bx and By out of the simulation and create a linear trend line for all sensors.

Note: *The mentioned accuracy in **Simulation results** can not be reached without a calibration.*

4.3 Differences in ATAN and ATAN2 calculation

In order to find a good linear approximation the ATAN or ATAN2 function can be used.

ATAN

ATAN can be used only for smaller ranges of movement (~±≤7mm) but has smaller errors compared to ATAN2. See ***Figure 55***.

The ATAN function is repeating and therefore may be not suitable for all ranges. Out of this reason a magnetic simulation can give a good estimation of the reachable linear range. In ***Figure 57*** and ***Figure 58*** an example of the modulation of ATAN is given.

$$\text{ATAN} = k \cdot \frac{Bx}{Bz}$$

k: The correction factor is used to linearize the ATAN or ATAN2 function.

ATAN2

ATAN2 can be used for higher ranges of movement (~≥±7mm), but gives higher errors. See ***Figure 55*** (right graph).

The ATAN2 is not repeating, see ***Figure 59***, ***Figure 60***

$$\text{ATAN2} = k \cdot \frac{Bz}{Bx}$$

k: The correction factor is used to linearize the ATAN or ATAN2 function.

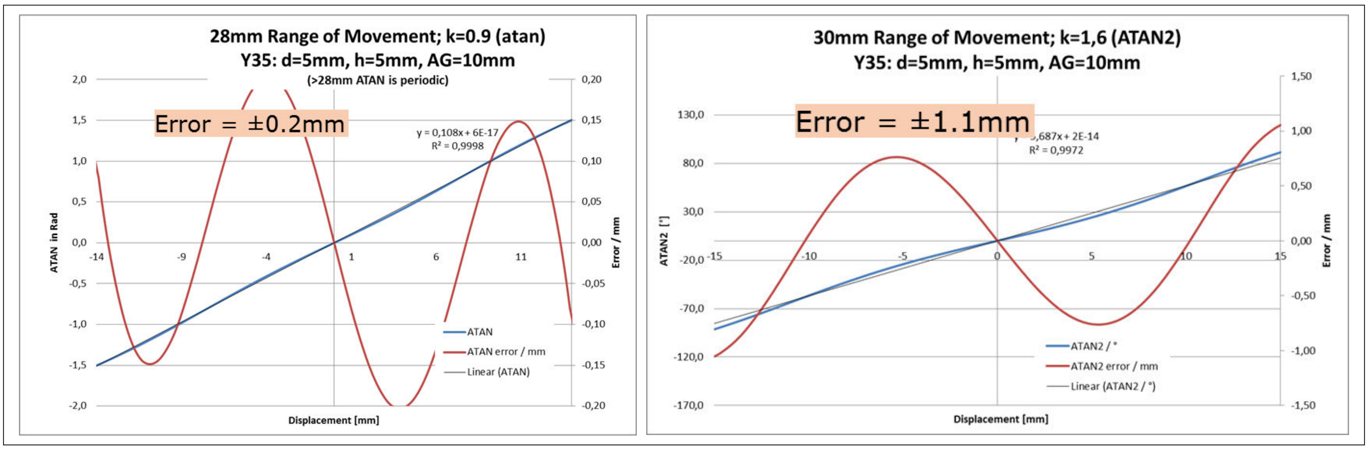

Figure 55 Example for difference of the use of ATAN or ATAN2 at nearly the same range of movement

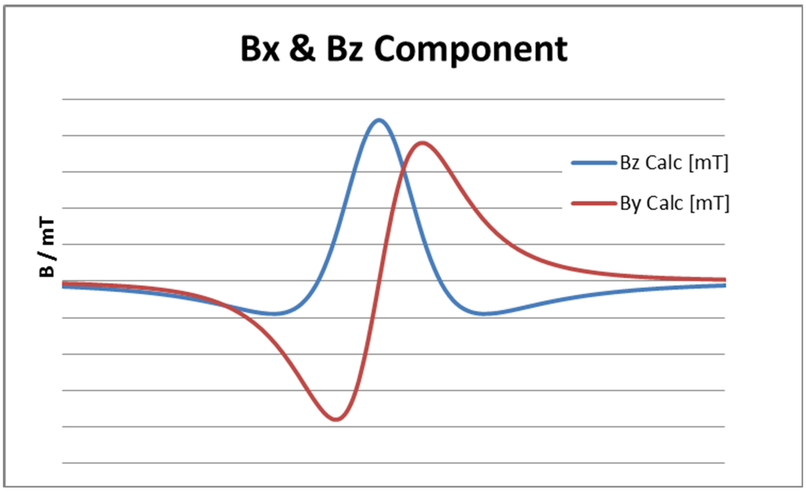

Figure 56

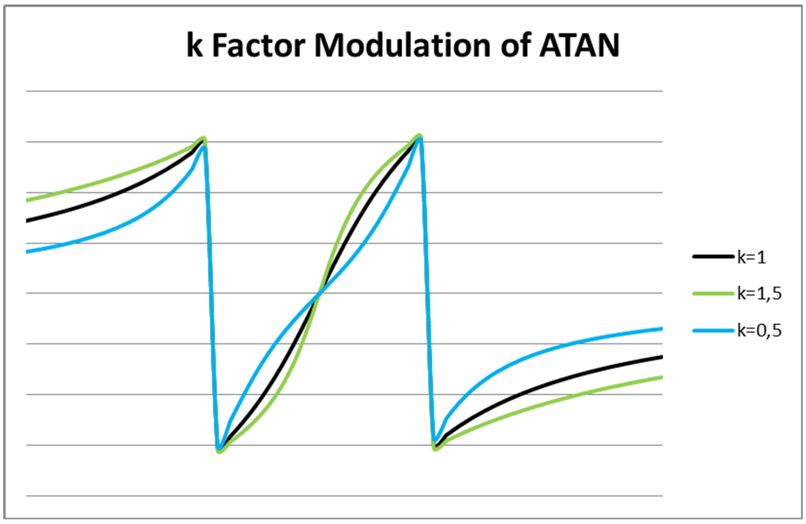

Figure 57

Figure 58

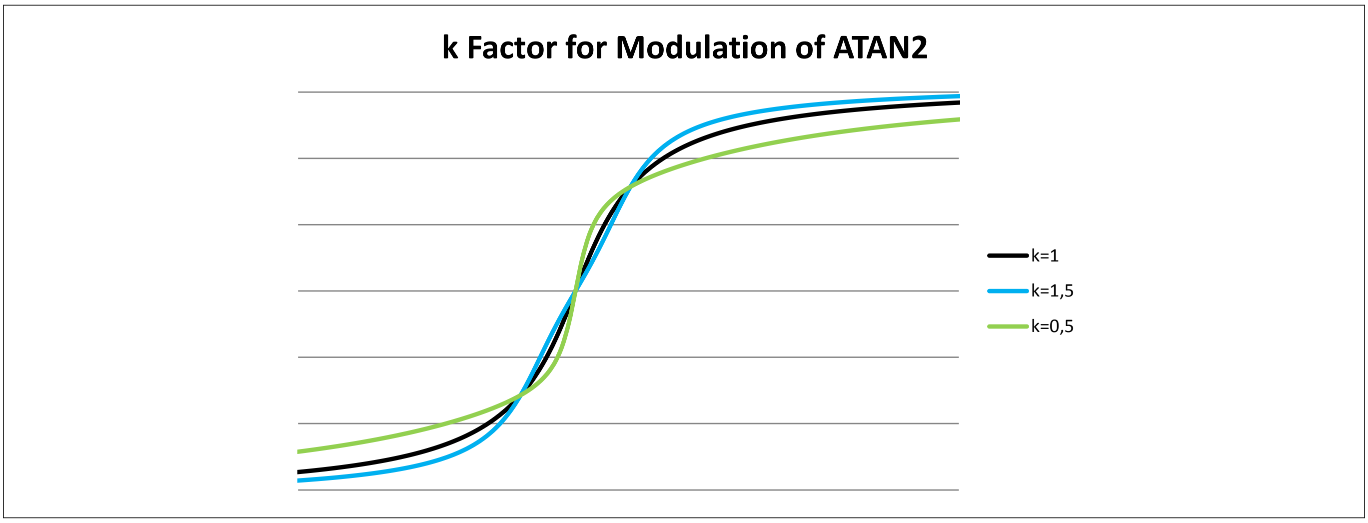

Figure 59

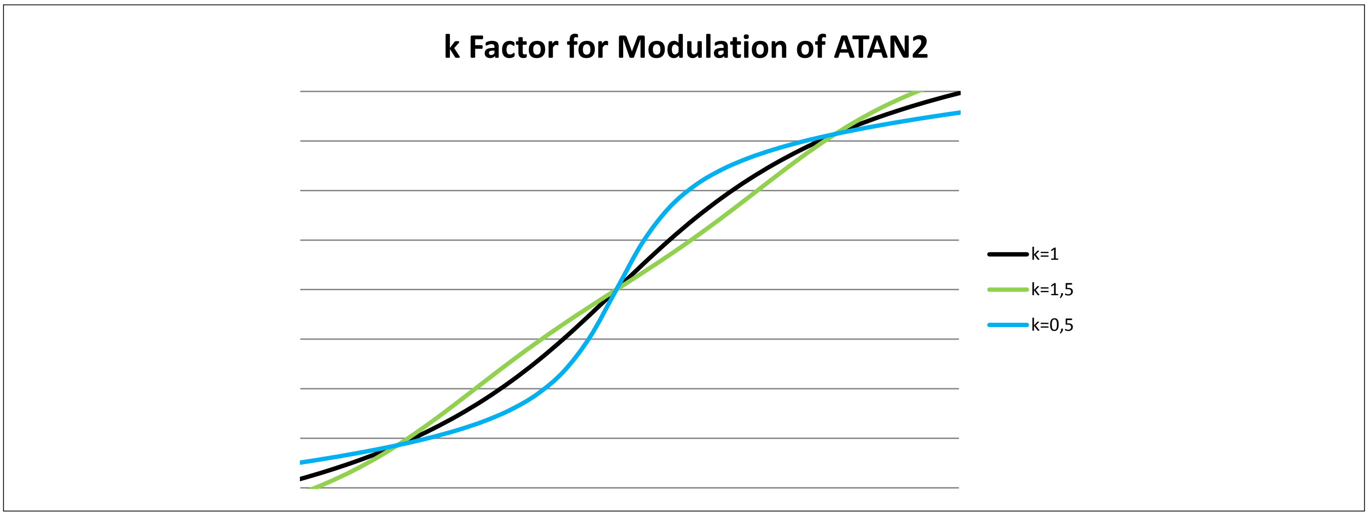

Figure 60

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Edition 2017-11-28

Published by

Infineon Technologies AG

81726 Munich, Germany

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Document reference
IFX-qbu1501137411229