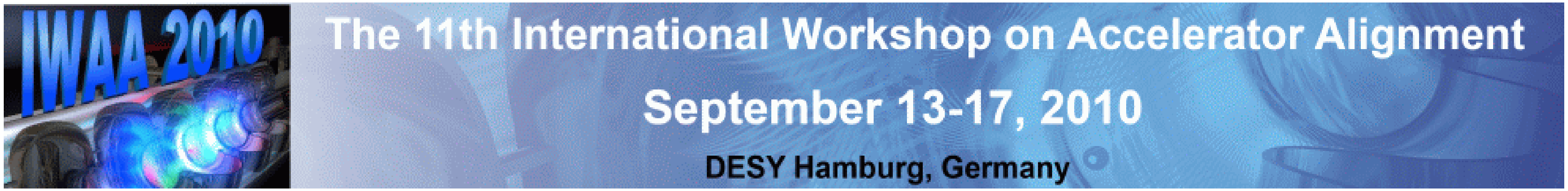


Invited talk on calibration:

Univ.-Prof. Dr.-Ing. Otto Heunecke

Institute of Geodesy, University of the Bundeswehr Munich

The geodetic calibration line of the UniBw Munich – Conception and implementation

Wednesday, September 15, 2010

Outline

1. **The new geodetic calibration line at Neubiberg**

   - Objectives, planning & design

   - Construction & side impressions

2. **Determination and documentation of measurand „length“**

   - Instruments & procedures

   - Influence factor “meteorology”

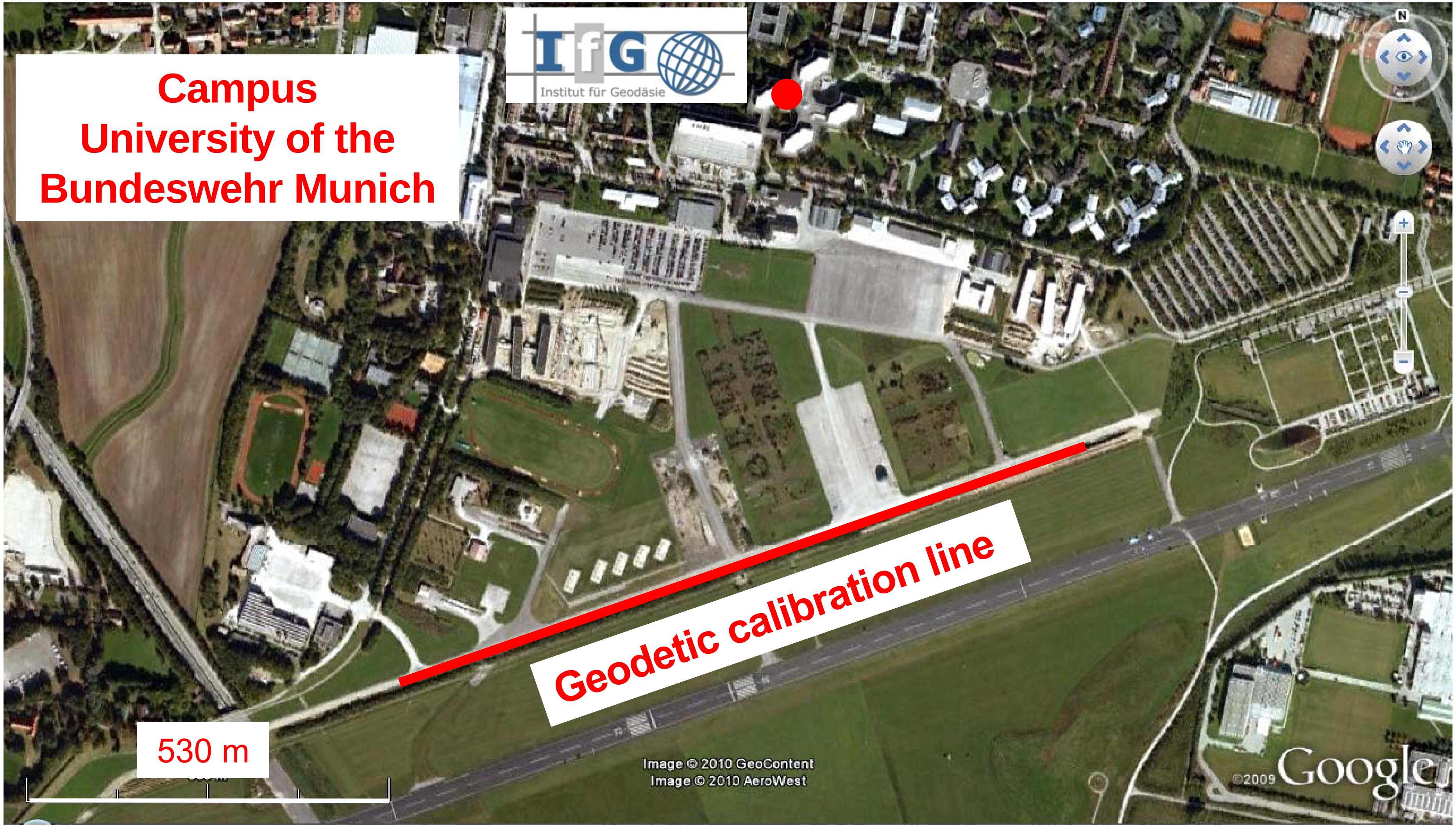
   - Calibration of low-cost meteo sensors

   - Use of geo sensor networks

   - Uncertainty of measurement: principles & implementation

3. **Conclusion and outlook**

1. The new geodetic calibration line at Neubiberg



Further information on the University please see: *www.unibw.de*

Objectives

For the calibration of EDMs, tacheometers, levelling instruments, gyros etc. certified Geodetic Laboratories are obliged to:

- Document and guarantee the traceability of the measurands (e.g. by intercomparison programmes);
- Document the obtained measurement uncertainty u of etalons.

Geodetic calibration line UniBw Munich:

Primary measurands: Length and azimuth

Goals:

$u_{distance}$ < 0.3 mm for distances up to 1100 m
(better for shorter distances, see comparator of Geod. Lab.)

u_{scale} < 0.2 ppm for distances up to 1100 m

$u_{azimuth}$ < 1 ´´

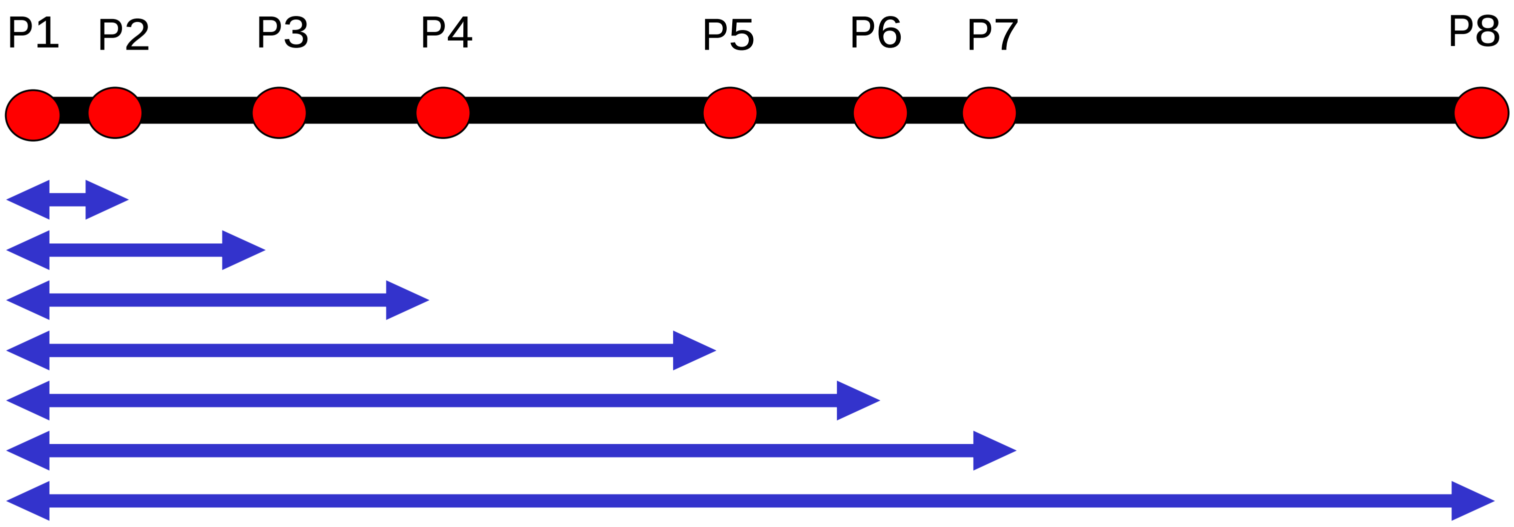
Secondary measurands: Coordinate differences

Design of calibration line

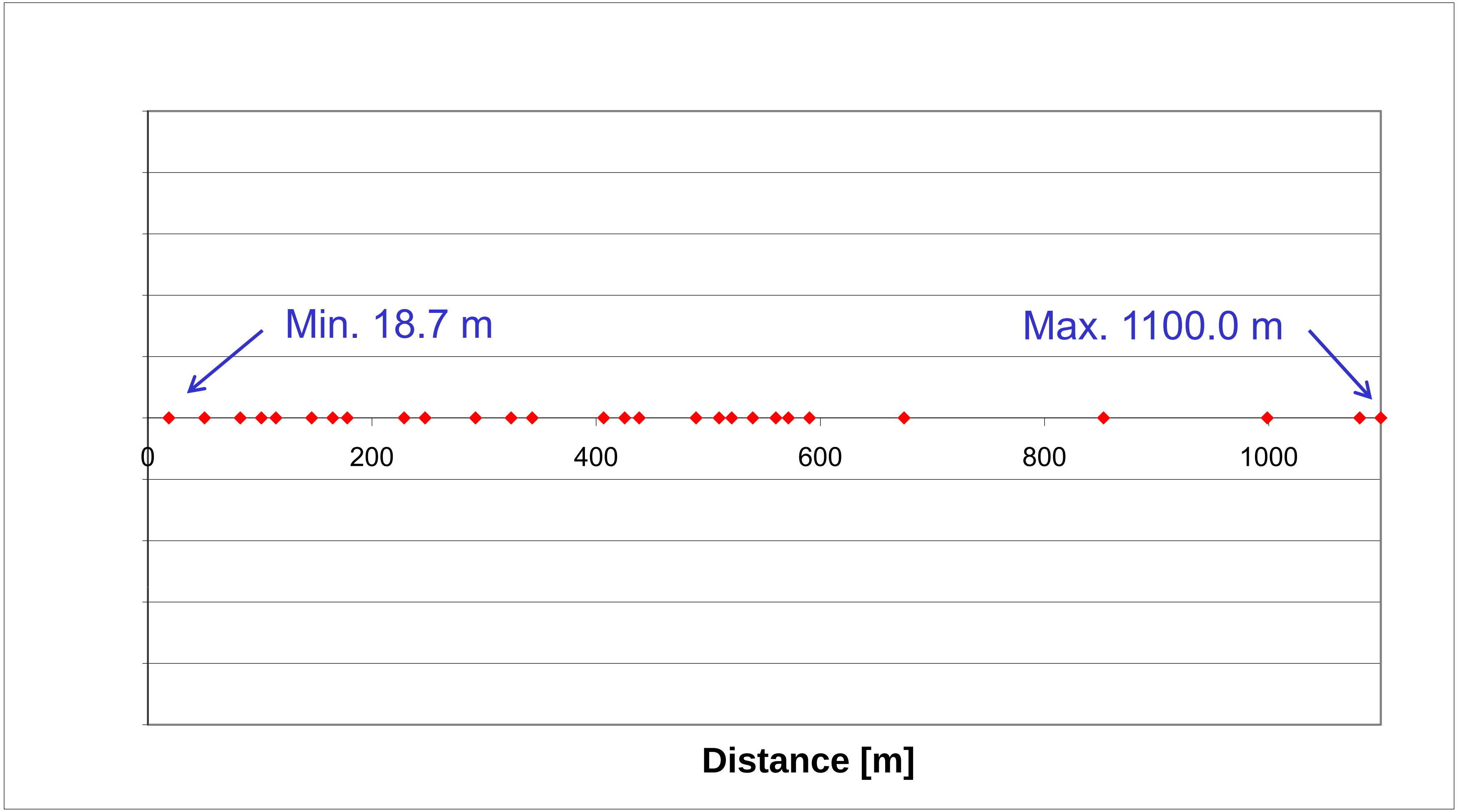
Schwendener Design

7 stations + 1 additional apart (P8)

		[m]	
Shortest distance	**A**	18.7	
Longest distance		1100.0	
1st design parameter	B	31,67	=1/15*(C-6A-U)
Total length 7 stations	**C**	590,3	=6A+15B+36D
2nd design parameter	D	0,08333	=1/36*U
EDM half wave length	**U**	3	



Distribution of distances over length



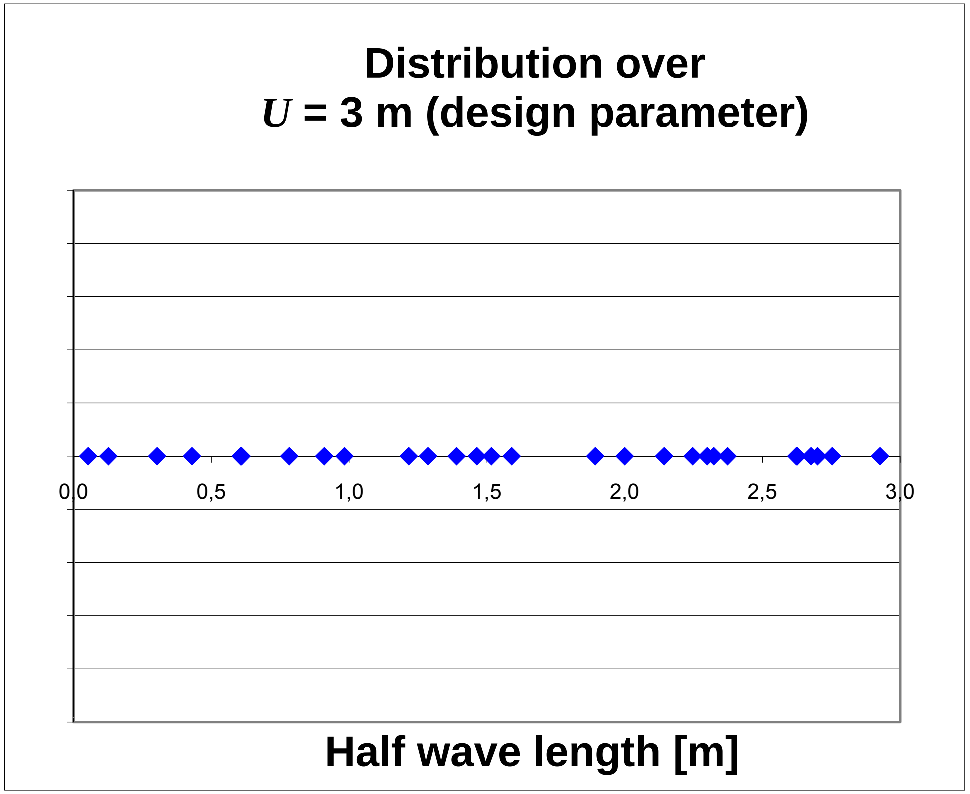
2 1 + 7 = 28 measureable distances

Distribution of distances over EDM half wave length

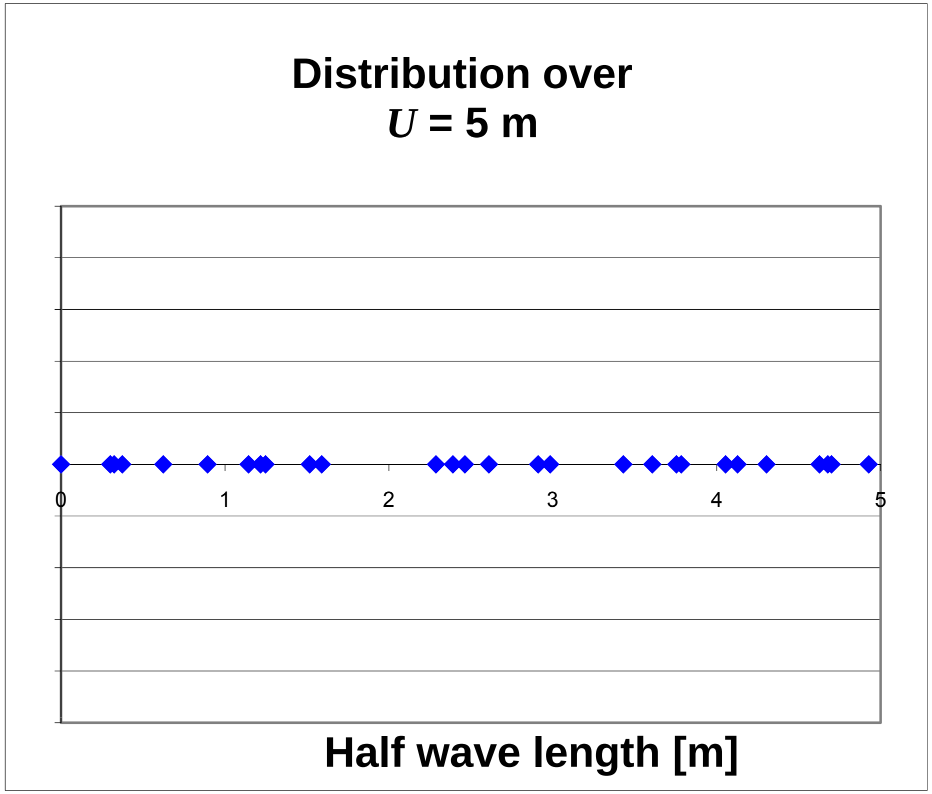
EDM half wave length $U\ [\mathrm{m}] = \frac{\lambda_M}{2} = \frac{c\ [\mathrm{m/s}]}{2 \cdot f_M\ [1/\mathrm{s}]}$ $\quad 15\ \mathrm{MHz} \leq f_M \leq 100\ \mathrm{MHz}$

Examples:

$f_M = 50\ \mathrm{MHz}$

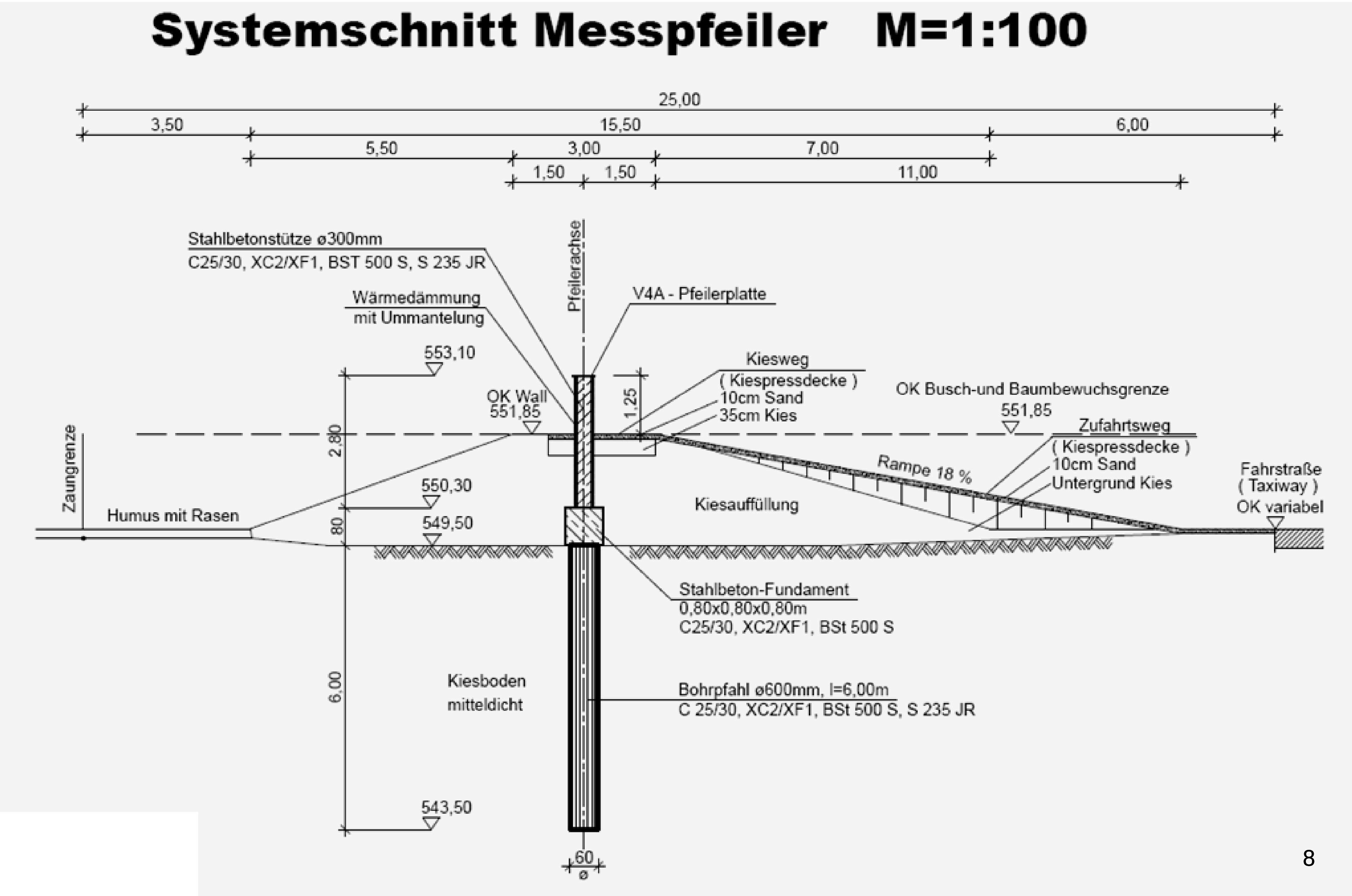


$f_M = 30\ \mathrm{MHz}$

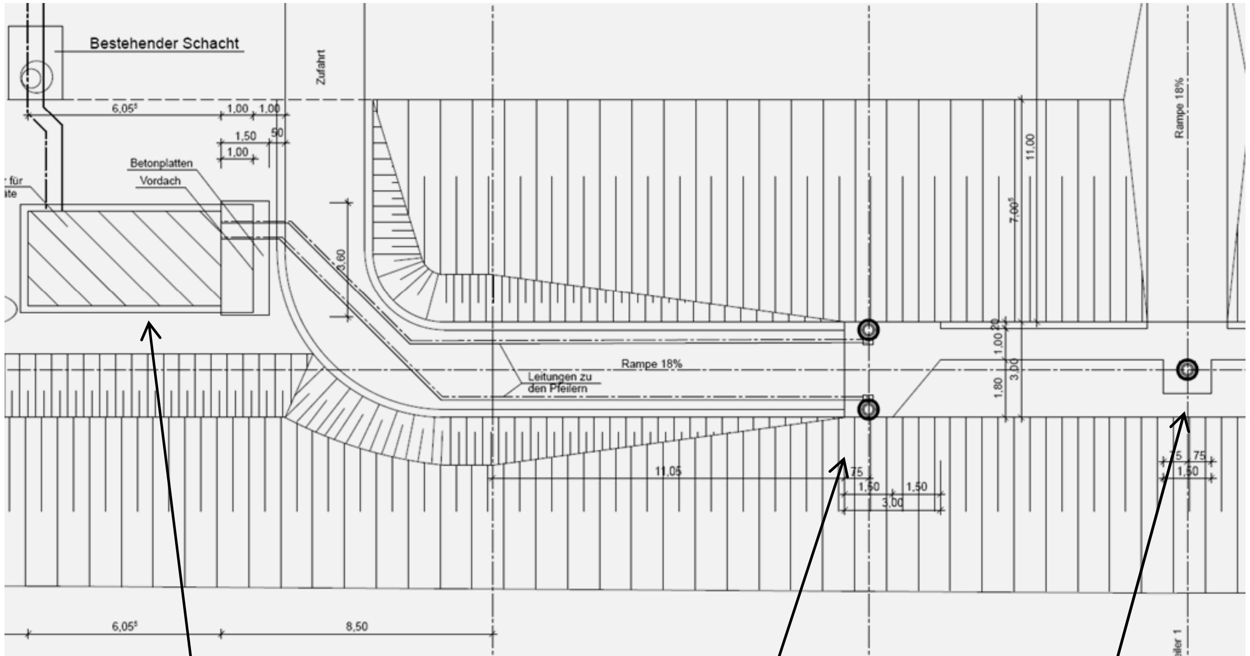


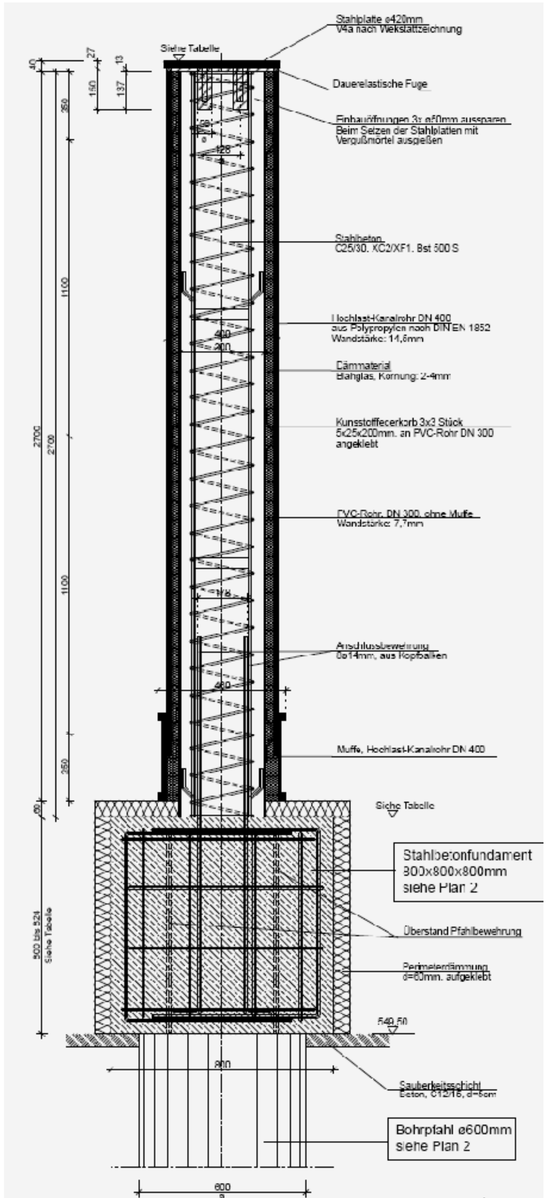
Construction of measurement pillars

Universität der Bundeswehr München



Construction details





Container for permanent measurement setups (230 V, Internet)

2 pillars for additional equipment

Measurement pillar No. 1

Impressions from construction works in 2008

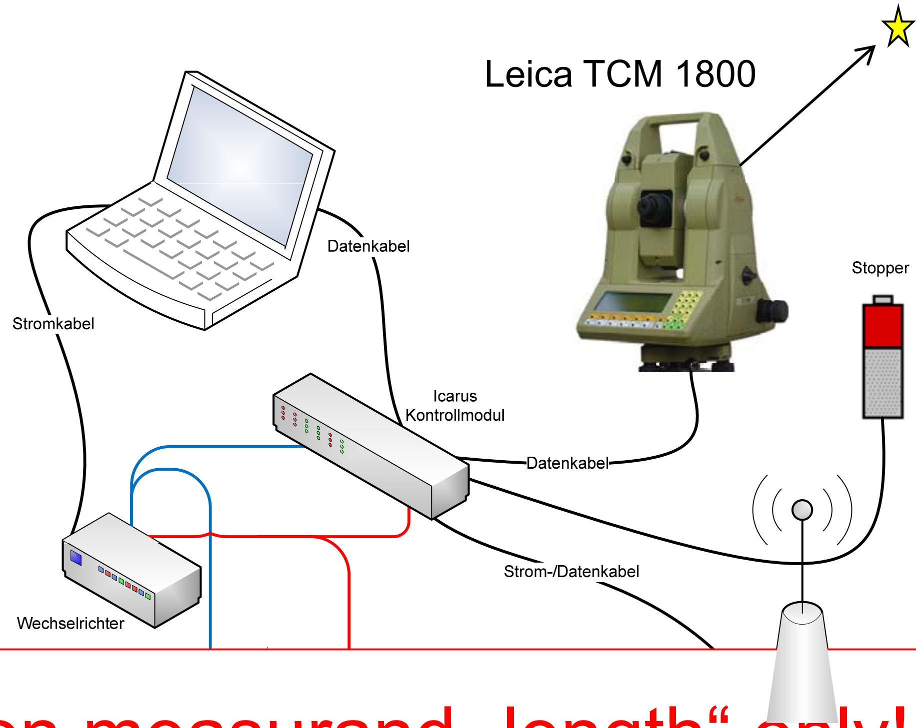
Impressions from recent status

Measurand "azimuth"

Gyro azimuth

DMT
DeutscheMontanTechnologie für Rohstoff · Energie · Umwelt

Gyromat 2000



Presentation is focused on measurand „length" only!

System „Icarus"

- Astronomical azimuth (pole star)
- Deflection of the vertical

GNSS azimuth

Equipment of Geodetic Laboratory

30 m interferometric longitudinal comparator:

- Interferometer HP 5507B
- Measurement uncertainty $u = (0.6 + 1.0 L_{[m]})$ µm
- Air-conditioned environments

Climate chamber:

- Temp. band -25°C – +45°C
- Aligned with comparator

Instruments for high quality distance measurements

Kern Mekometer 5000

EDM

Leica TDA 5005

Tacheometer

Leica AT901-LR

Tracker

Leica System 1200

GNSS

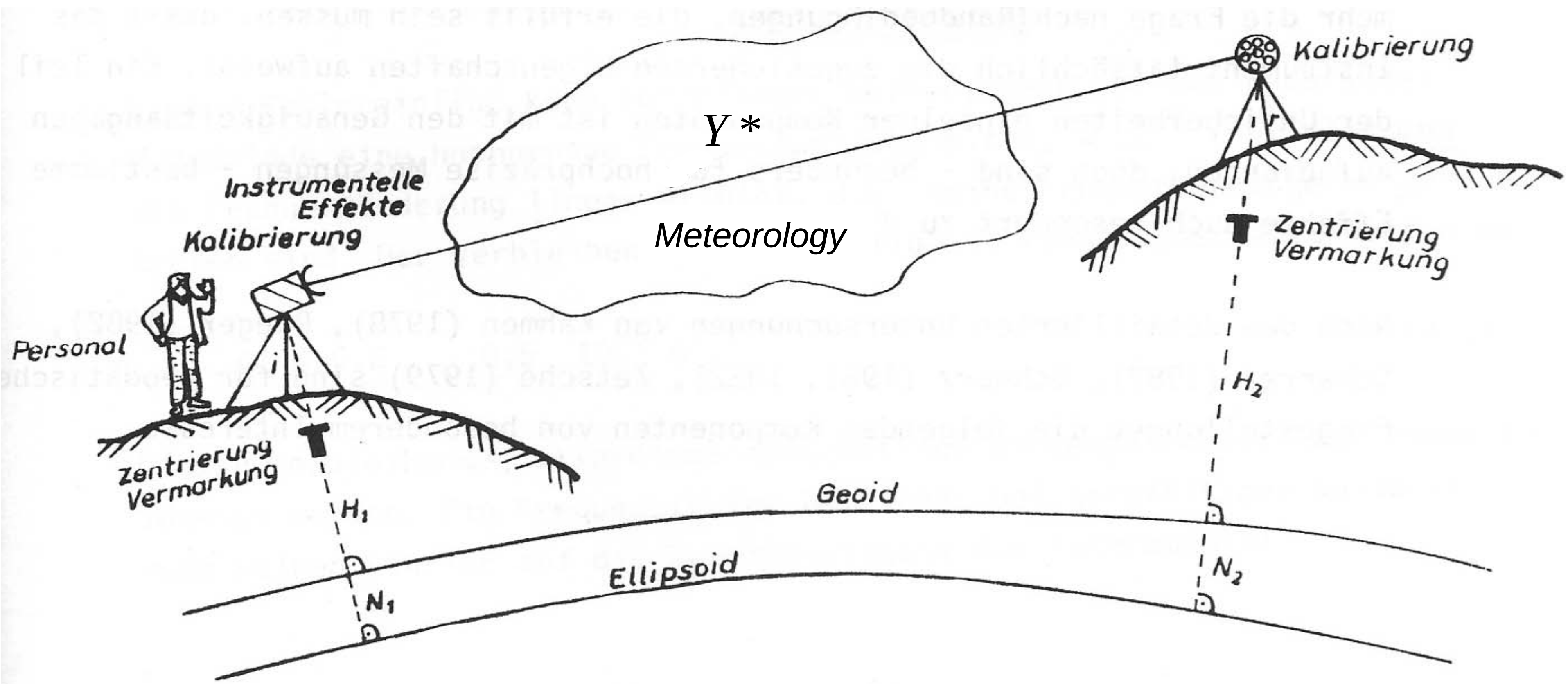
Leica AT401

Still to be done!

Leica Geosystems

HEXAGON METROLOGY

2. Determination of measurand „length“ by EDM



Y^* : Uncorrected „raw“ observation

Niemeier, W.:
Zur Zuverlässigkeit geodätischer Systeme – Problemformulierung und Lösungsansätze.
Wiss. Arbeiten der Fachrichtung Vermessungswesen, Nr. 153, Hannover, **1989**

Functional and stochastical model of evaluation

Functional model: $Y = Y^{*} + \sum_{j=1}^{p} c_j + \sum_{j=1}^{q} r_j \quad = \quad f(Y^{*}, \boldsymbol{X})$

- (Scalar) Result of measurement: Y
- Uncorrected observation: Y^{*}
- Correction for all recognised systematic effects (corrections c & reductions r): $\sum_{j=1}^{p} c_j + \sum_{j=1}^{q} r_j$

Each correction is a function of some influence factors X_i , i = 1, … N,
e.g., temperature and adds a respective percentage to the variance of the result.
Even "centering" etc. can be seen as a correction c_c with E(c_c) = 0 and σ_c^2.

Stochastical model: $\boldsymbol{\Sigma} = \begin{vmatrix} \boldsymbol{\sigma}^2_{raw} & \boldsymbol{O} \\ \boldsymbol{O} & \underset{N,N}{\boldsymbol{\Sigma}_{XX}} \end{vmatrix}$ — Co-variance matrix of influence factors ($\boldsymbol{\Sigma}_{XX}$)

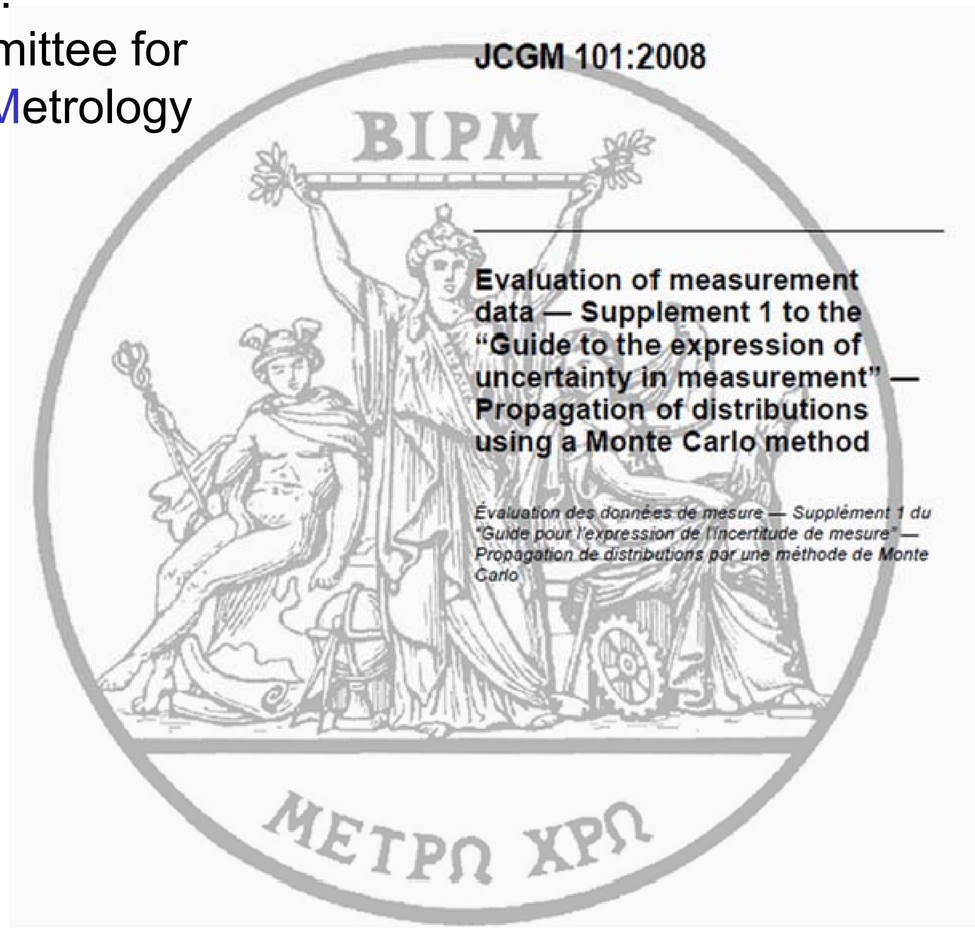
Variance of result Y: $\sigma_Y^2 = \sigma^2_{raw} + \boldsymbol{F}\,\boldsymbol{\Sigma}_{XX}\,\boldsymbol{F}^T , \qquad \boldsymbol{F} = \left(\frac{\partial f(Y^{*}, \boldsymbol{X})}{\partial \boldsymbol{X}} \right)$

Produced by:
Joint Committee for
Guides in Metrology


JCGM 100:2008
GUM 1995 with minor corrections

Evaluation of measurement data — Guide to the expression of uncertainty in measurement

Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure


JCGM 101:2008

Evaluation of measurement data — Supplement 1 to the "Guide to the expression of uncertainty in measurement" — Propagation of distributions using a Monte Carlo method

Évaluation des données de mesure — Supplément 1 du "Guide pour l'expression de l'incertitude de mesure" — Propagation de distributions par une méthode de Monte Carlo

BIPM

Bureau International
des Poids et Mesures

Download of documents see:

www.bipm.org

Uncertainty of measurement u:

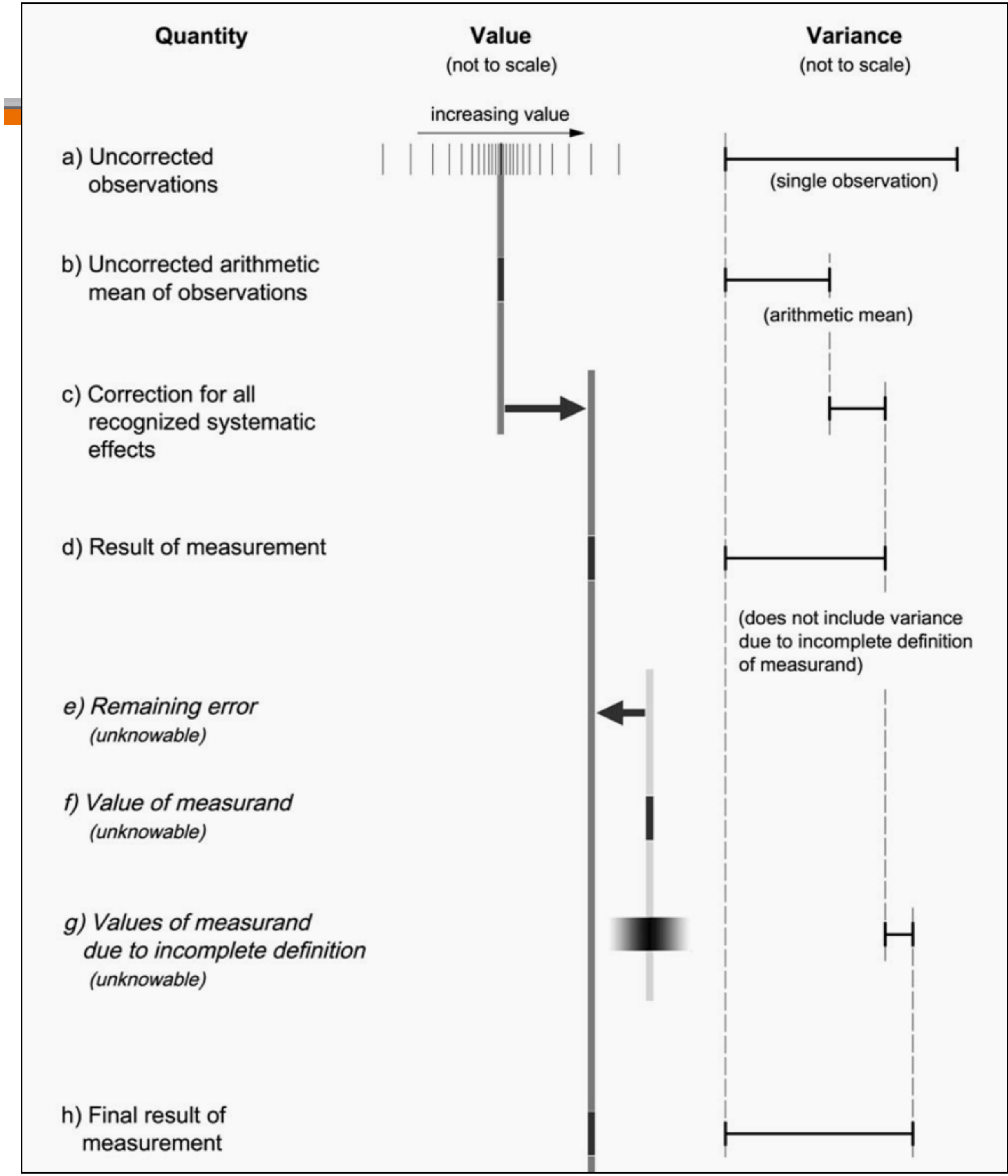
Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Uncertainty of measurement comprises many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.

Principles to obtain u:

- Analytical deduction (law of error propagation, Bayes theorem);
- Numerical studies: Monte-Carlo-Simulation (see JCGM 101:2008);
- Intercomparison programmes and their combined evaluation.

Essential: Consideration of influence factors X_i , i = 1, … N ; N : complete.



Graphical illustration of values, error, and uncertainty

See JCGM 100:2008, Annex D, p. 53

Complete result:

$$Y \pm k \cdot u \,;$$

k : factor, often $k = 2$

Influence of meteorological correction on EDM

$$dn \times 10^6 = -1.00dt + 0.28dp - 0.04de$$

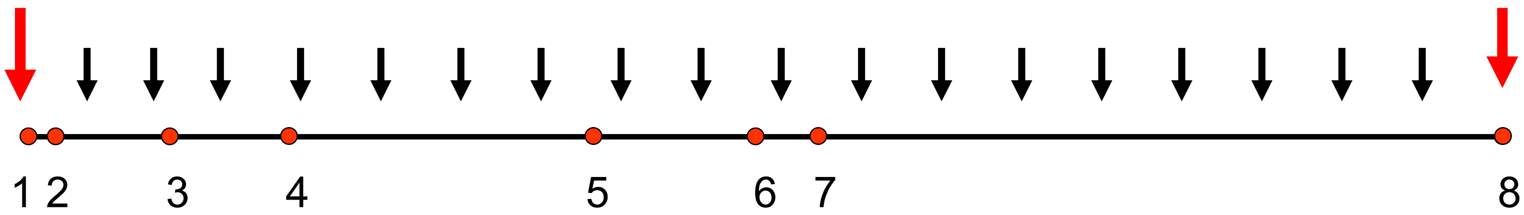
- dt : variation of temperature [°C]
- dp : variation of air pressure [hPa]
- de : variation of partial water vapor pressure [hPa], with

$$e = \frac{rF\ [\%]}{100} E$$

rF : rel. humidity, E : saturation vapor

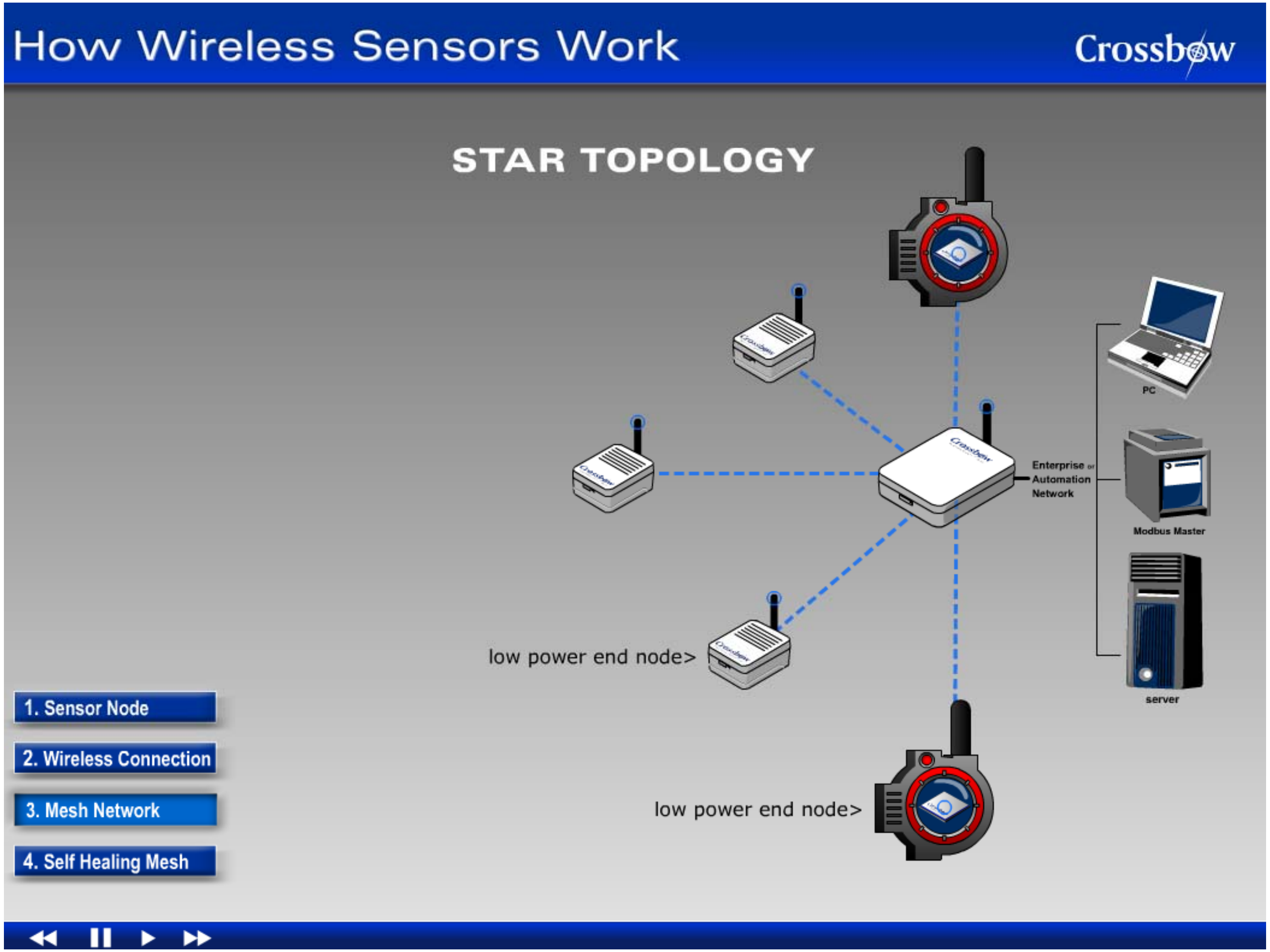
Demand for 0.1 ppm:

t with 0.1 °C, p with 0.3 hPa, rF with 10% representative for signal path requested!



Alignment of 20 units for integral determination of t , p and rF

Principle of geo sensor networks



Crossbow mote with sensor board MT420

approx. 3 x 5 x 4 cm

Mote with integrated devices:

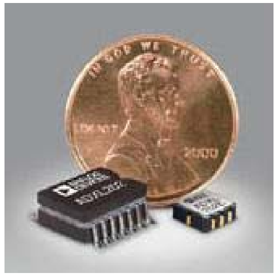
- 1 Dual axis accelerometer
- 1 Light sensor
- **1 Barometer**
- **1 Temperature- und humidity measuring unit**
- 1 Low-cost GPS receiver
- 64 Kbyte EEPROM, TinyOS & ISM radio module

Crossbow

www.xbow.com

Accelerometer

- Type ADXL202JE (MEMS Technology)
- Range ±2 g
- Resolution 2 mg
- Rate 60 Hz
- Nonlinearity 0.2%
- “Zero g bias level 2.0 mg/°C from 25°C“



www.analog.com

ANALOG DEVICES

Light sensor

- Type TAOS TSL2550D
- Range 400–1000 nm
- 1 channel for IR
- 1 channel visible light
- 12 bit resolution
  „Lux to bit“

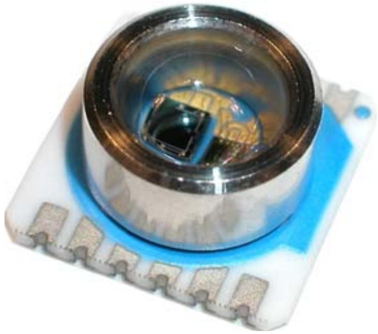
TAOS TEXAS ADVANCED OPTOELECTRONIC SOLUTIONS®

www.taosinc.com

Meteo sensors at Crossbow board MT420

Barometer

- Type Intersema MS5534AM
- Range 300 – 1100 hPA
- Resolution 0,01 hPA
- **„Accuracy ± 1.5% at 25°C“**



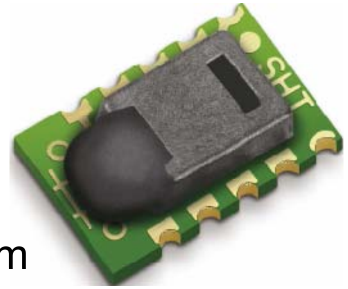
∅ ca. 3 mm

intersema
a measurement specialties company

www.intersema.ch

Temperature- and humidity meas. unit

- Type Sensirion SHT11



ca. 7,5 x 5 x 2,5 mm

Temperature:
- Range -40 to + 80°C
- **„Accuracy ± 0.5°C at 25°C“**

Humidity:
- Range 0 – 100% Rel. humidity (RH)
- Resolution 0,3% RH
- **„Absolute RH accuracy ± 3.5% RH“**

www.sensirion.com

SENSIRION
THE SENSOR COMPANY

Location unit at Crossbow board MT420

www.u-blox.com

Ca. 17 x 22.4 x 3 mm

- GPS 16 channels L1 C/A Code
- Rate 4 Hz
- NMEA output, support DGPS & WAAS
- External antenna
- Accuracy

Accuracy	Position	2.5m CEP	according µBlox
	DGPS	2.0m CEP	

Accuracy specifications of Crossbow meteorological units:

t with $\pm$ 0.5 °C, p with $\pm$ 1.5 hPA, rF with $\pm$ 3.5% at 25°C

Low-cost sensors for high accuracy application?

Goal: Enhancement by factor 5 by calibration with respect to t and p .

Recording of reference values for calibration

Thommen-Meteo-Station HM30

t, p, rF

Universal meteo unit Almemo 2590-3S

t, p, rF

Quartz thermometer 2804A

t

Digiquarz Barometer 760

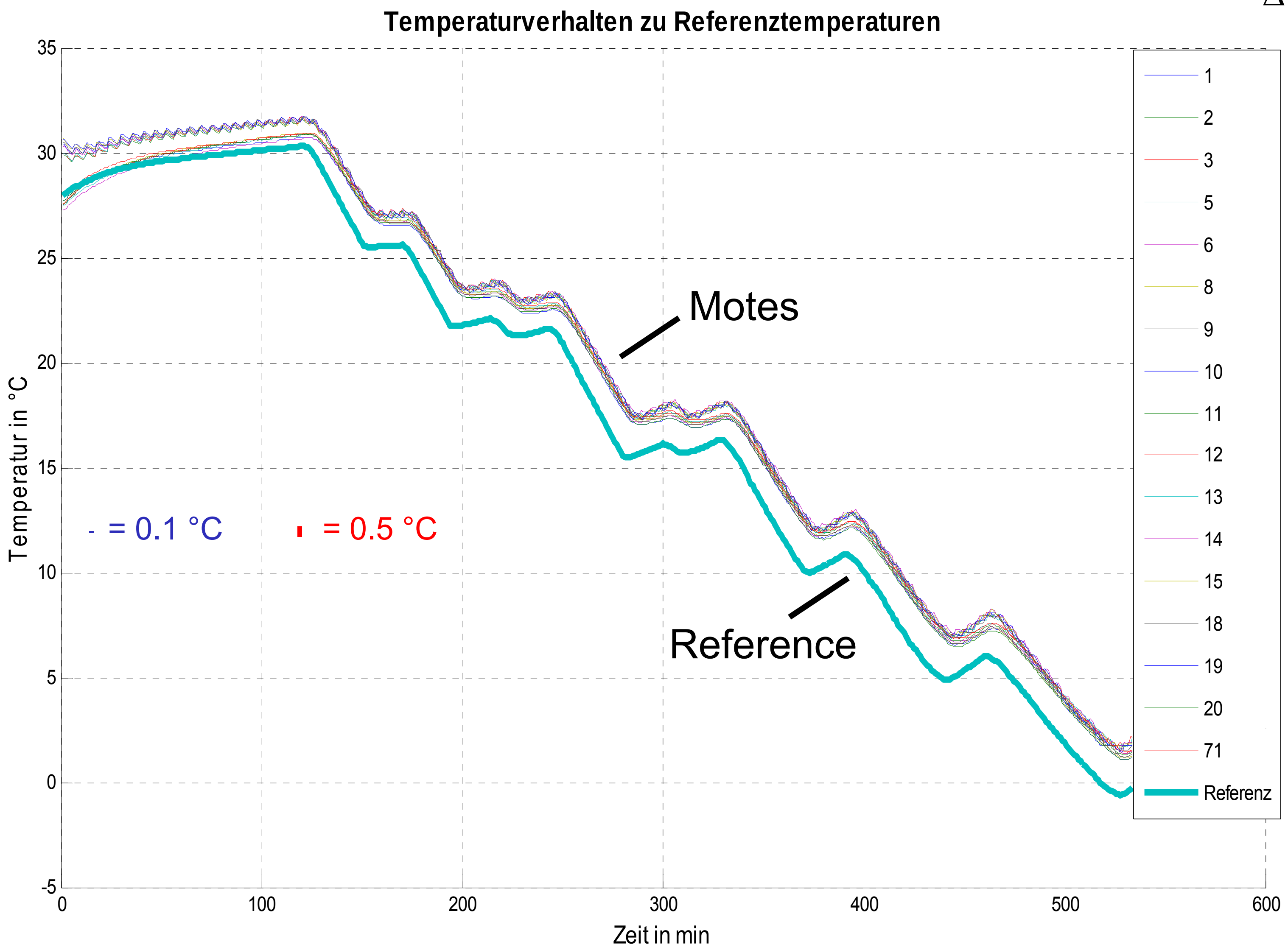
p

Climate chamber

Reference instruments by factor 10 better then crossbow MT 420 test items

Investigations with respect to *t*

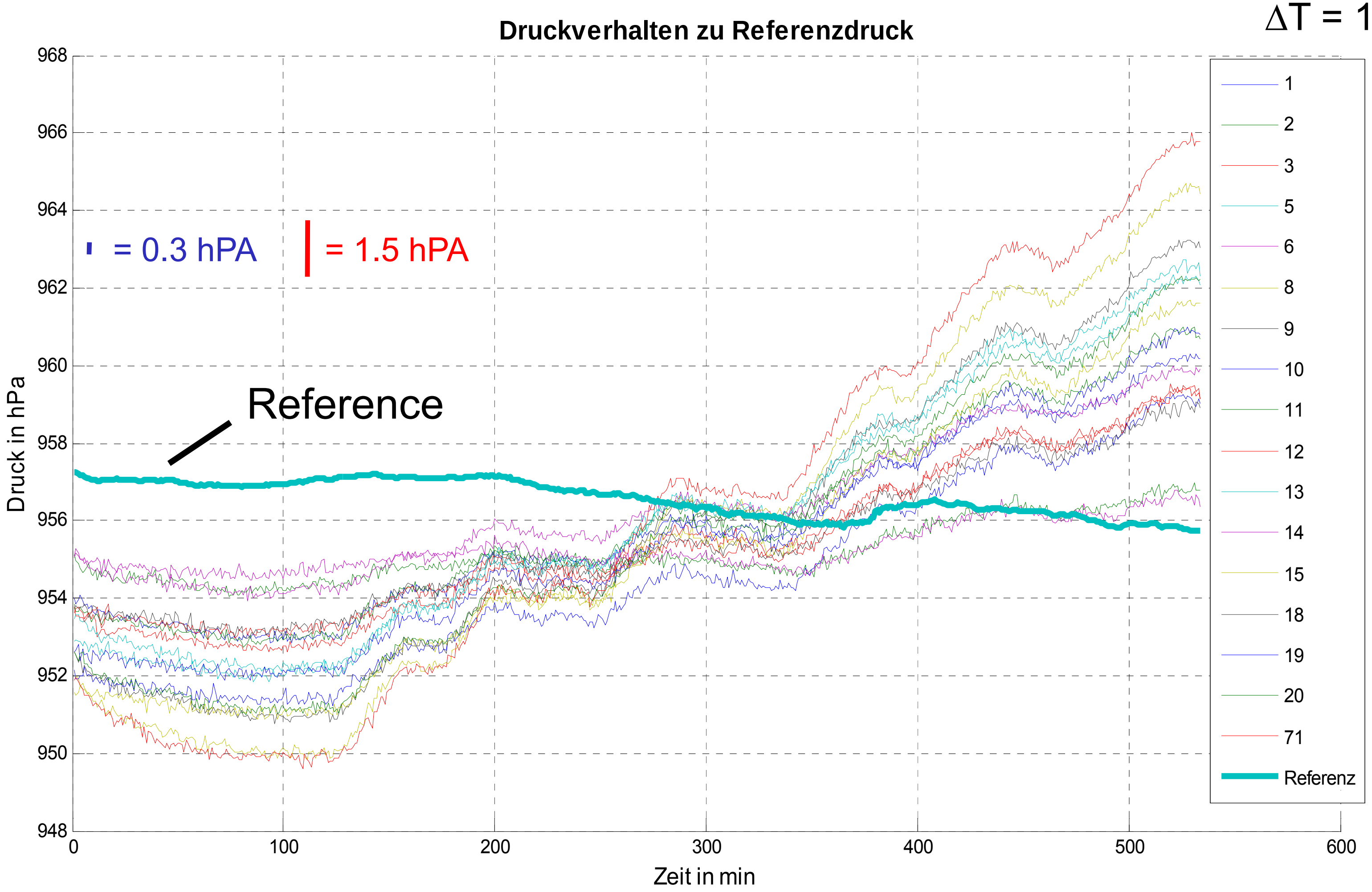
ΔT = 1 min.



Investigations with respect to *p*

Universität der Bundeswehr München

ΔT = 1 min.

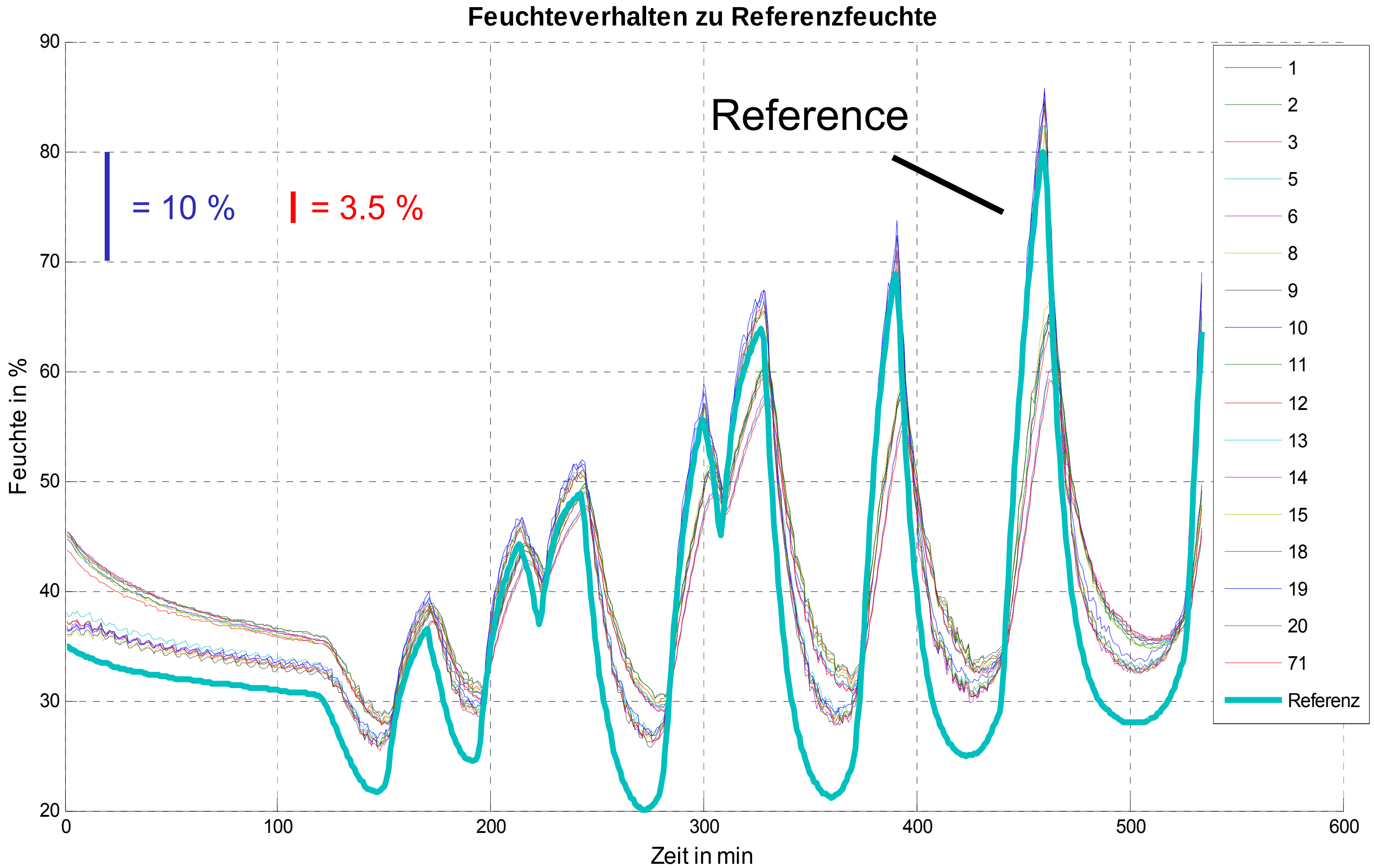


Pressure units depict a certain dependence to temperature.

Investigations with respect to *rF*

Universität der Bundeswehr München

ΔT = 1 min.

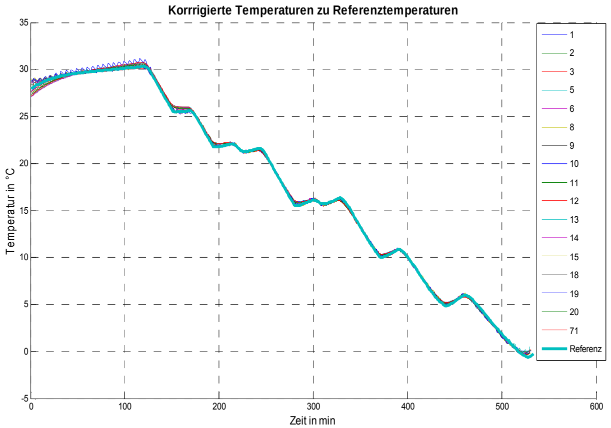


Rel. humidity at climate chamber varies due to regularization of temperature.

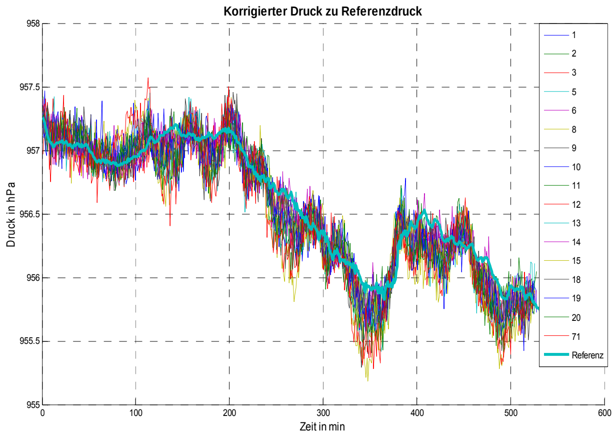
Noticeable time lag of humidity units.

Calibration results of Crossbow meteo sensors

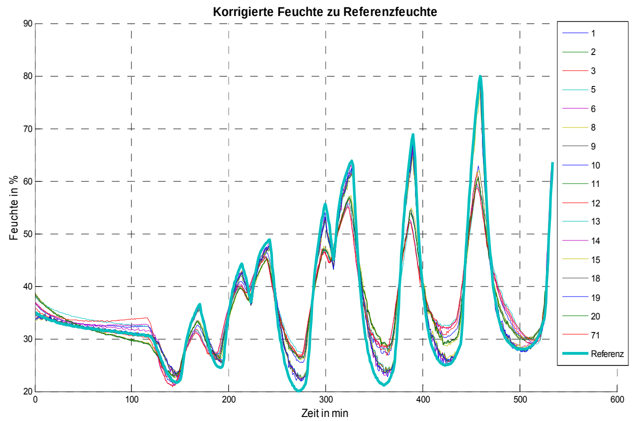
- Several calibrations performed (t = 0 – 30 °C) to evaluate long term stability.
- 3 of 20 motes with bad and unreliable results.
- Determination of individual response curves using regression analysis.



cal. temp. vs. true



cal. pressure vs. true



cal. rel. humidity vs. true

RMS (simple regression)		
Temperature °C	Pressure hPa	Rel. humidity %
0.23	**0.11**	**3.85**

* : Improved later by a polynomial regression

Determination of reference distances by ME 5000

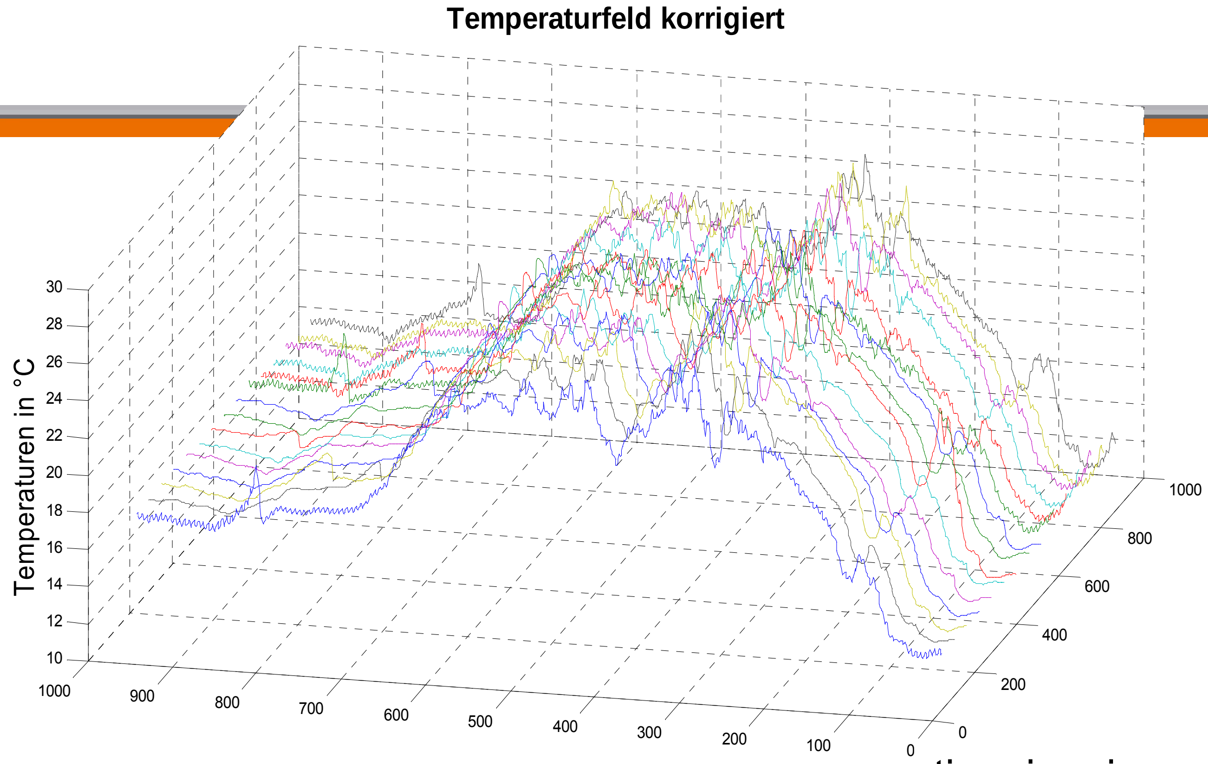
Kern Mekometer ME 5000

- Variable frequency 460 – 510 MHz
- U = 0.3 m (half wave length)
- Accuracy: 0.2 mm + 0,2 ppm
- Range: 5000 m

Set up of Crossbow motes

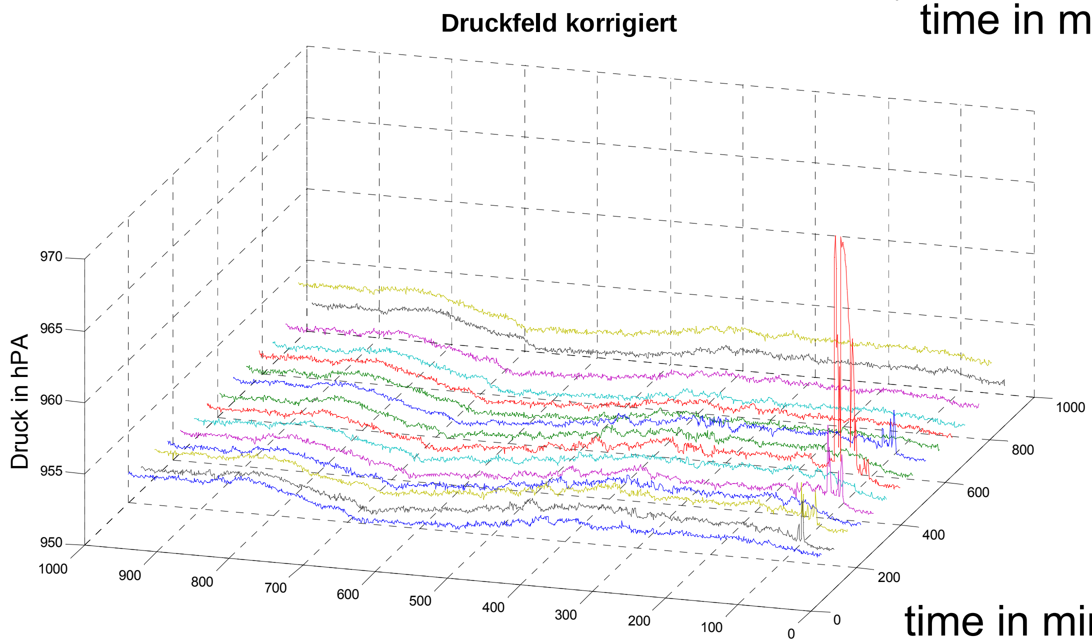
der Bundeswehr
Universität München

ΔT = 1 min.



distance in m

time in min



distance in m

time in min

Spatial temporal determination of temperature and pressure field

during ME 5000 measurements

Uncertainty budget ME 5000

Influence factor X_i	Assumption for distribution	Influence	Measurement uncertainty u
Additional value of instrument	normal	additive	**0,14 mm**
Scale factor of instrument	normal	proportional	**0,50 ppm**
Meteorological correction	normal	proportional	0,14 ppm
Eccentricity of prism	rectangle	additive	0,02 mm
Resolution of instrument	rectangle	additive	0,02 mm
Inclination of prism	rectangle	additive	0,03 mm
Misalignment of prism	normal	additive	0,005 mm

Uncertainties of additional value u_c and scale factor u_s are from the old calibration line.

Uncertainty of scale factor is dominant (and must be improved)!

Influence of meteorological correction relatively low compared to u_c and u_s.

Determination of reference distances by AT901-LR

Leica laser tracker AT901-LR

MPE: Maximum permissible error

Approx.: MPE = U = 2 u

Absolute distance measurement (ADM),
interferometric distance measurement (IFM)

Specified measurement uncertainty ADM:
Distance: U = $\pm$ 10 μm *+ ppm?*

Modulation frequency: 900 MHz
Max. range: 80 m (volume 160 m)

- New and certified instrument
- Re-calibrated according to NIST at Geodetic Lab.

From a Leica brochure:

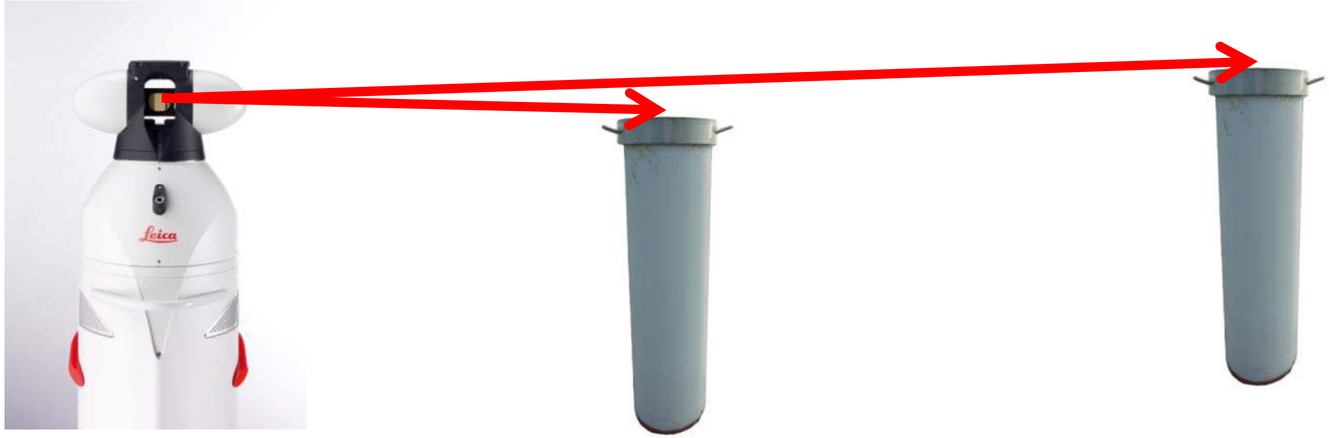
In-Line Distance Measurement

Range (m)	ADM (mm)	IFM (mm)	ADM (mm)	IFM (mm)
	MPE values		Typical values	
2 to 5	0.0141	0.0011	0.0071	0.0006
2 to 10	0.0141	0.0025	0.0071	0.0013
2 to 20	0.0141	0.0054	0.0071	0.0027
2 to 30	0.0141	0.0084	0.0071	0.0042
2 to 35	0.0141	0.0099	0.0071	0.0050
2 to 40	0.0141	0.0114	0.0071	0.0057

Possible configurations for AT901-LR

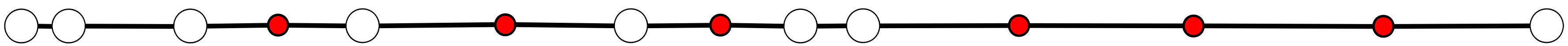
Simplified functional model:

$$Y = Y_2 - Y_1$$



$$Y = Y_1 + Y_2$$

Use of intermediate points if Y_i > 75 m (out door situation):



Uncertainty budget AT901-LR

Influence factor X_i	Assumption for distribution	Influence	Measurement uncertainty u
Additional value of instrument	normal	additive	5 µm
Scale factor of instrument	*normal*	*proportional*	???
Meteorological correction	normal	proportional	**0,14 ppm**
Production accuracy corner cube: circularity	rectangle	additive	2 µm
Production accuracy corner cube: surface	rectangle	additive	3 µm
Error of alignment	rectangle	additive	5 µm
Stability set up	rectangle	additive	6 µm

Meteorological conditions are most crucial for measurement uncertainty of AT901-LR.

Uncertainty budget much better than ME 5000.

Scale factor of instrument uncertainty actually not considered.

Unfavorable error propagation for set ups with intermediate points.

Preliminary results

Distance	Estimated value [m]	Measurement uncertainty u ME 5000 [mm]	Measurement uncertainty u AT901-LR [mm]
1-2	18,78???	0,295	0,016
2-3	82,45???	0,295	0,023
3-4	146,14???	0,300	0,029
4-5	177,97???	0,305	0,063
5-6	114,29???	0,298	0,026
6-7	50,62???	0,297	0,017
7-8	509,69???	0,432	0,120

3. Conclusion and outlook

- Results obtained so far at the calibration line UniBw Munich are only preliminary.

- Intercomparison programmes with participation of several geodetic institutions ongoing and open to any other interesting party.

- Workshop on the final results and possibilities of the new calibration line scheduled for Spring 2011.

- Documentation of complete results according to GUM is obligatory for Geodetic Laboratories – and also any other metrology institutions.

- Principles of GUM are known in Geodesy since years, but a full adaption is still outstanding.

- Consideration of all relevant influence factors on the interesting messurands is essential in today's metrology; see meteorology on EDM's.

Thank you very much for the invitation!