PTB Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

EURAMET

EUCoM
Evaluating Uncertainty in Coordinate Measurement

EMPIR 17NRM03 EUCoM
Seminar 29.06.2021, online

Application and results

Session 3

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Working Group 5.34 “Multisensor Coordinate Metrology”

Overview

- **Part 1: Round Robin**
  - Scope of the validation study

- **Part 2: Reference standards & Measurements**
  - Selection criteria
  - Reference standards
  - Measurement strategies

- **Part 3: Implementing the new methods**
  - Software tools to calculate EUCoM measurement uncertainties

- **Part 4: Results**

- **Conclusion & Outlook**

Part 1: Round Robin

Round robin: Objectives

- **OBJECTIVE:**
  - **Collect many and diverse datasets for method validation**

- **Some constraints**
  - Each participant had to measure at least…
  - 1 **prismatic** standard
  - 1 **freeform** standard

- **Not a traditional round robin**
  - Not about the best possible measurement / low uncertainty
  - Instead: Different uncertainties or measurement “qualities”
  - Calibration / reference data was provided by consortium members
  - All data was shared openly

Round Robin: Logistics

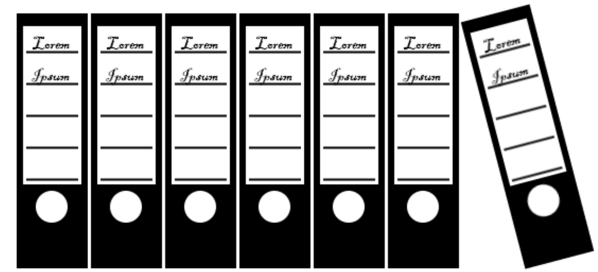
- **Participants**
  - 14 partners
    - Different labs
    - Different CMMs (with different accuracy)

- **Unexpected hurdles**
  - Brexit
    - Added a “surprise” customs border
  - COVID-19 pandemic
    - Lock-downs restricting lab access and slowing work

Original source: Wikimedia commons

Round Robin: Outcome

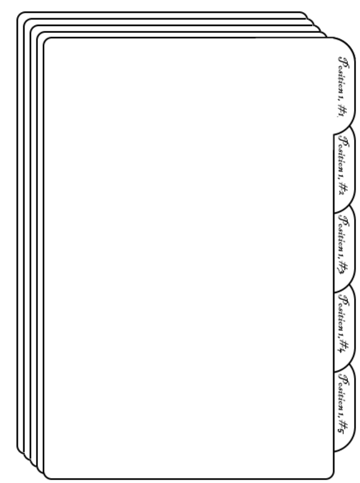
- **Outcome**
  - Collected 30+ complete datasets
  - More than originally planned
  - Every partner was able to contribute at least one dataset
  - Archived data will be made available after the project



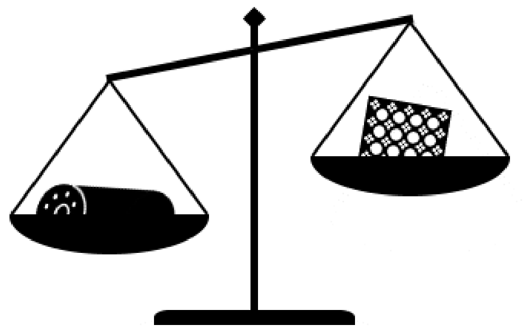
- **A “complete” partner dataset comprises:**
  - Five repeat measurements
  - Measurement in four orientations (for method A)
  - Sphere and gauge block measurement (for method A)
  - Point clouds and vectors (for method B)

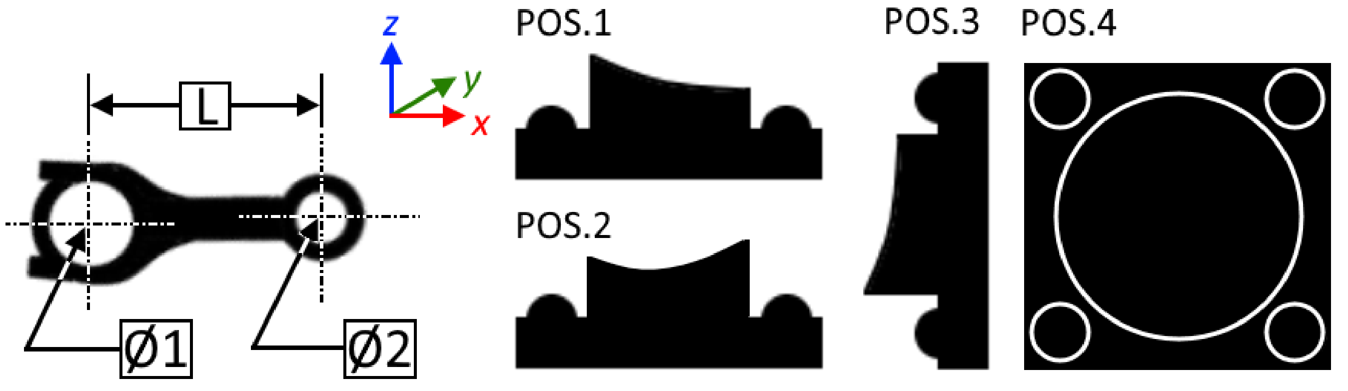
→ This equates to hundreds of measurements

→ Lots of raw data available for EUCoM and future research



Part 2: Reference standards & Measurements





Standards: Selection criteria

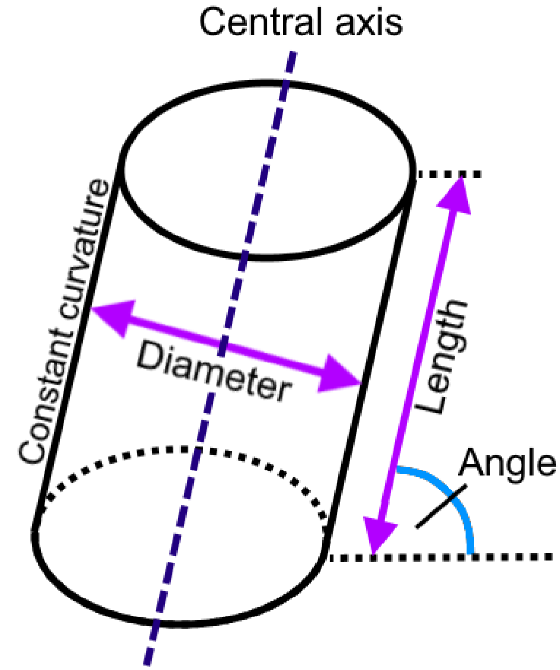
- **PROJECT REQUIREMENT:**
  - **One prismatic and one freeform reference standard**

- **Additional requirements (defined during the selection process):**
  - Size range: 100 - 500 mm (~300 mm)
    – Use a larger CMM volume to magnify uncertainties (e.g. positioning)
  - At least five different measurand types
    – General method demonstration
    – Representative sample of “common” measurands
  - At least some industrial workpieces
    – Avoid using only “research artefacts”
    – EUCoM is intended for industry application

Prismatic vs. Freeform

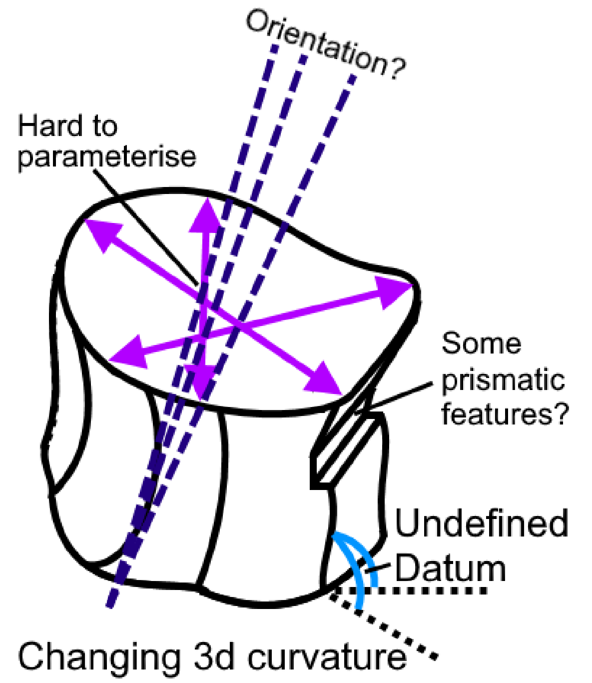
- **An aside about the artefact types**

- **Prismatic artefacts:**
  - Based on standard geometries
    – Spheres, cylinders, planes …
  - Easy to describe
    – Simple mathematical models
    – Usually just a few parameters
  - Geometries and measurands are well-defined (including normals)
    – Diameter, parallelism, …



Prismatic vs. Freeform

- **Freeforms artefacts**
  - No standard models for freeforms/sculptured surfaces
  - Description by model approximations
    - E.g. splines, rarely a parameterised equation (f(x,y,z))
    - Parameters are hard to define
    - Models are often limited to a small region of a surface
  - “Complete” measurement requires high point density
    - Reliance on prior knowledge (e.g. normals)
    - Result may be affected by quality of prior knowledge
  - Evaluation is less straight-forward
    - E.g. comparing profiles or points
    - Feature-based registration becomes more difficult
    - Much easier to register based on simple features like spheres, flat planes



Prismatic vs. Freeform

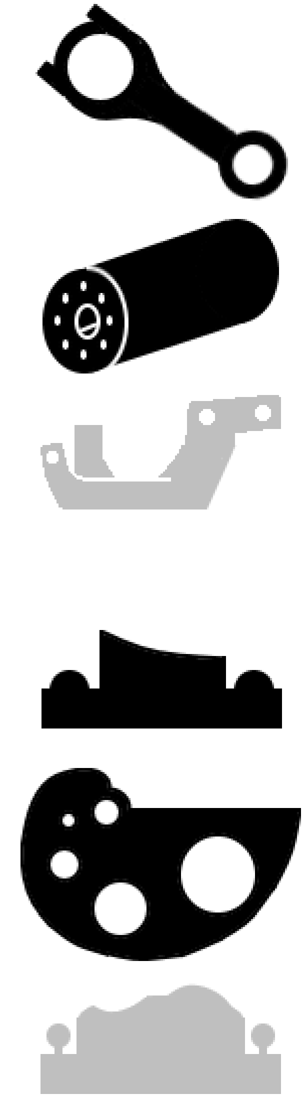
- **Why is this distinction important?**
  - Freeforms have a number of advantages over prismatic designs:
    – Enable more compact or efficient designs, e.g. merging several functions in one part
    – Relevant to manufacturing industries, e.g. automotive, medical, optics

- **Evaluation strategies for freeforms can be very different**
  - Need to demonstrate that EUCoM methods also work for freeforms
  - Can’t be limited to prismatics

Reference standards: Selection

- **Six reference standards were selected**
  - 3x prismatic
  - 3x freeform
  - Broad range of measurands
  - Greatly improved flexibility in planning during the pandemic

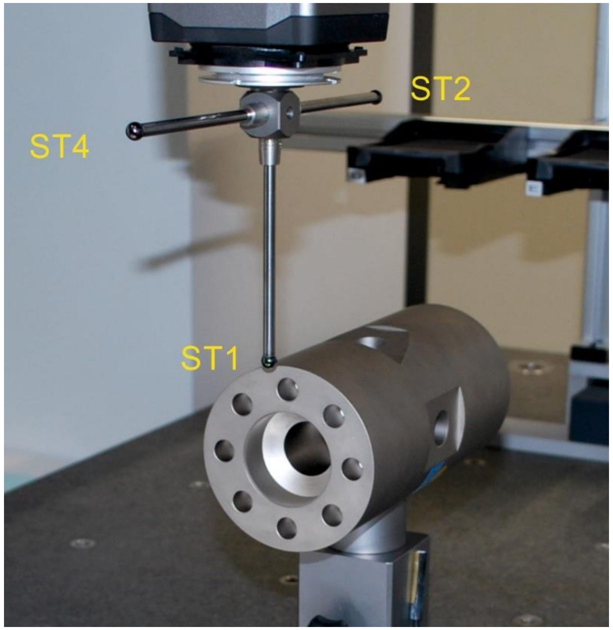
- **Pandemic problems**
  - The first lockdown hit towards the end of the calibration phase
  - Some reference standards became inaccessible
  - Calibrations and / or measurements couldn’t be completed



Reference standards: Prismatic

- **Multi-feature check (MFC)**
  - Designed as reference standard for CMMs
  - 50 features, 19 measurand types to choose from

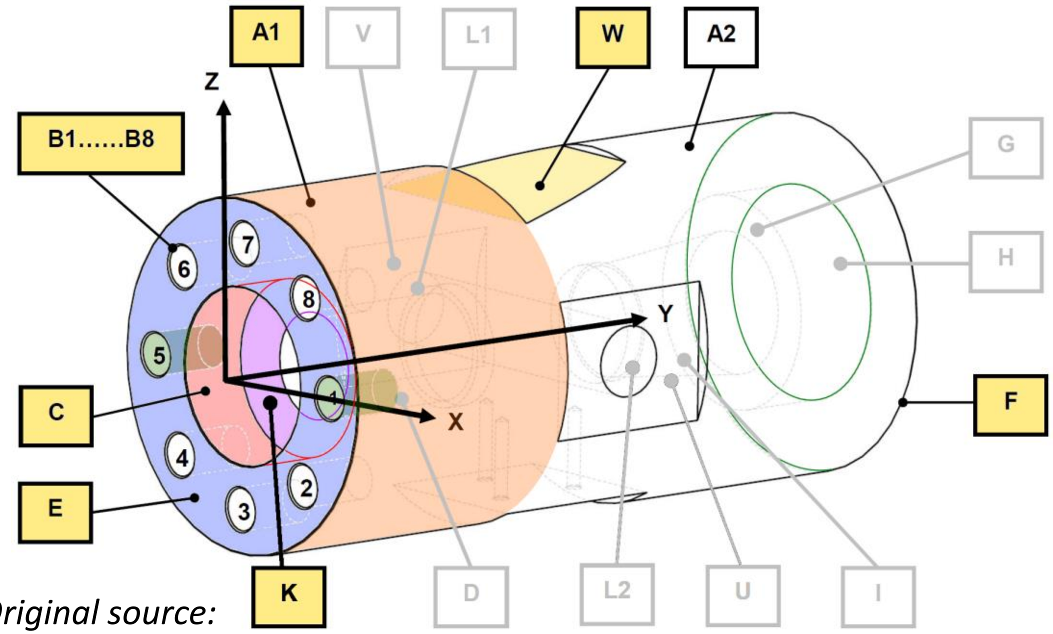
    → Plenty of variety
  - Two specimens were circulated
  - One was of “lower quality” due to age and wear



Multi-feature check
(200 x 100 mm l x d)

- **Measurands:**
  - Selected features to cover form, dimensions and positioning
  - 17 measurements chosen
  - Wanted to avoid overloading this standard with too many tasks

Reference standards: Prismatic



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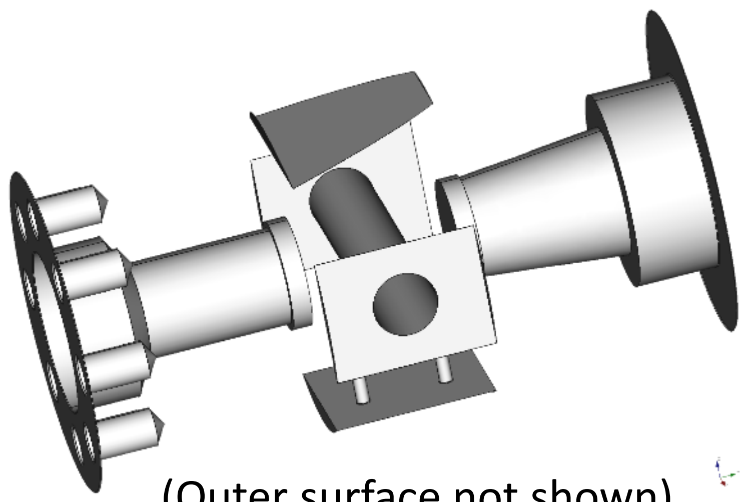
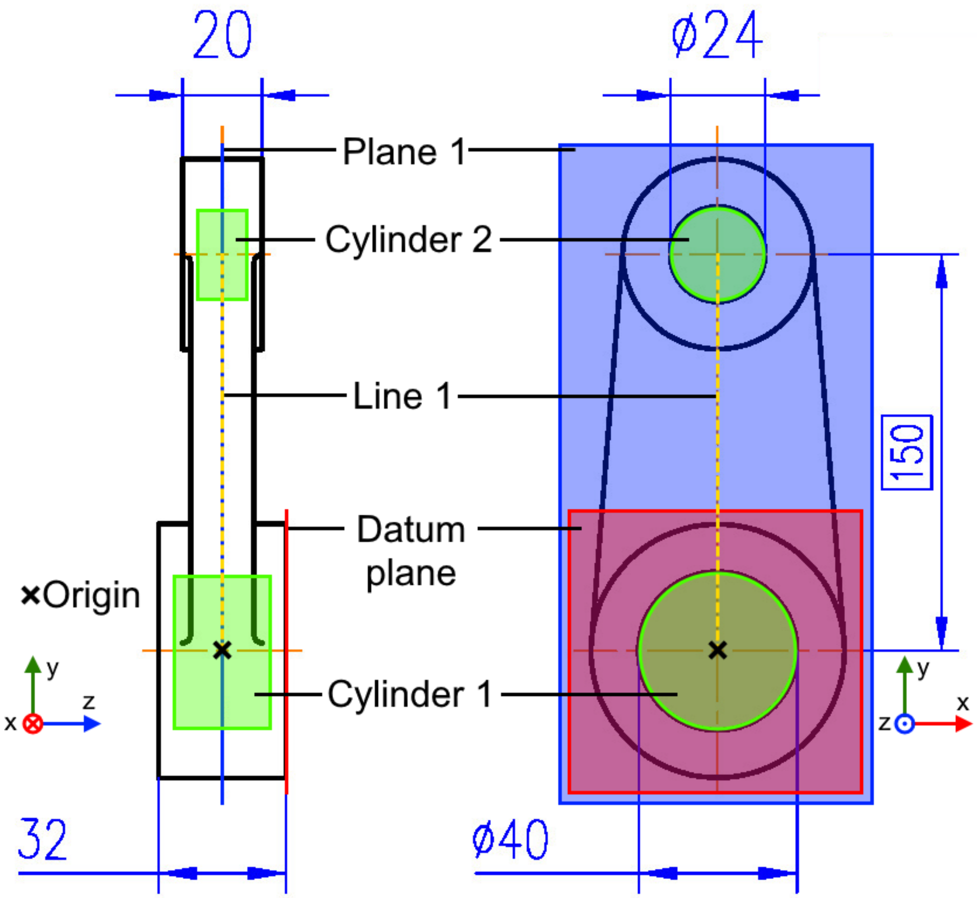


(Outer surface not shown)

Name	Geometry	Measurands
A1	External cylinder	surface straightness, roundness, cylindricity, diameter
B1, B5	Two internal cylinders	distance between holes
C	Internal cylinder	diameter and form, perpendicularity to E, concentricity, radial and total radial runout to A1
E, F	Two planes	flatness, distance, parallelism
K	Internal cone	diameter, cone angle, parallelism to A2
W	Inclined plane	Angularity to A1

Reference standards: Prismatic

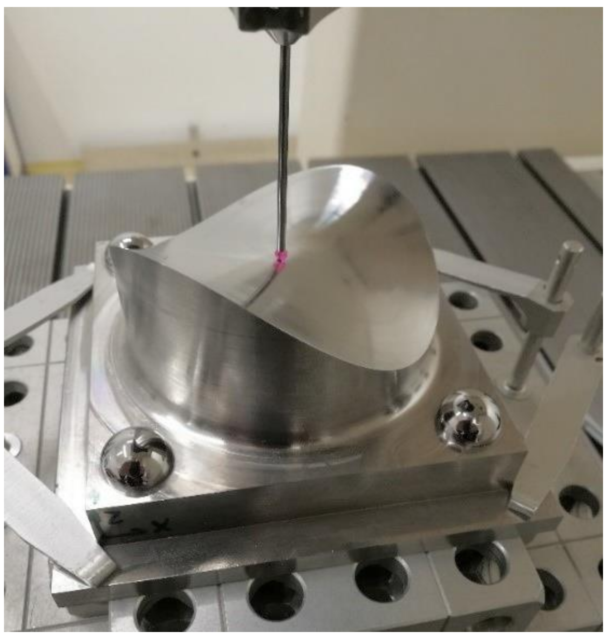
- **Connecting rod**
  - Manufactured part
  - Chosen for its simplicity
  - Measurands
    - Cylinders, diameters and distance
    - Parallelism between cylinder axes
    - Orthogonality of cylinders to plane 1

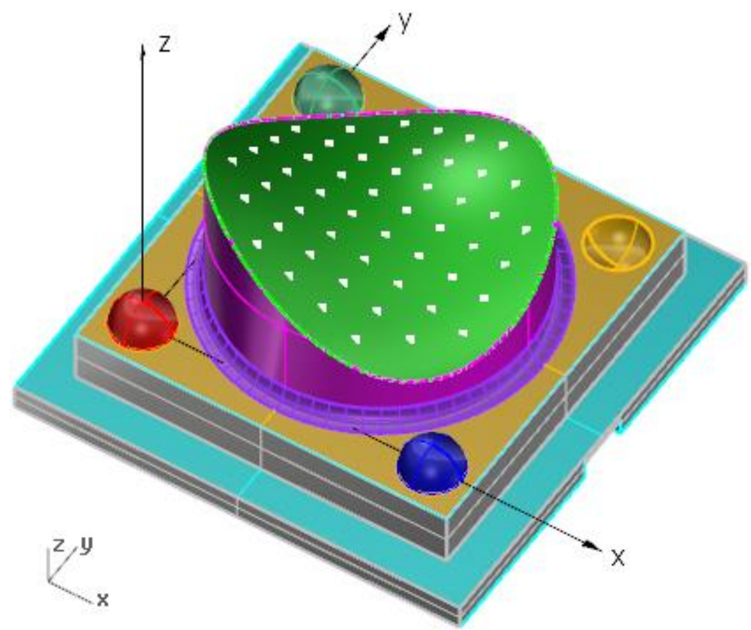


Source: CMI

Reference standards: Freeform

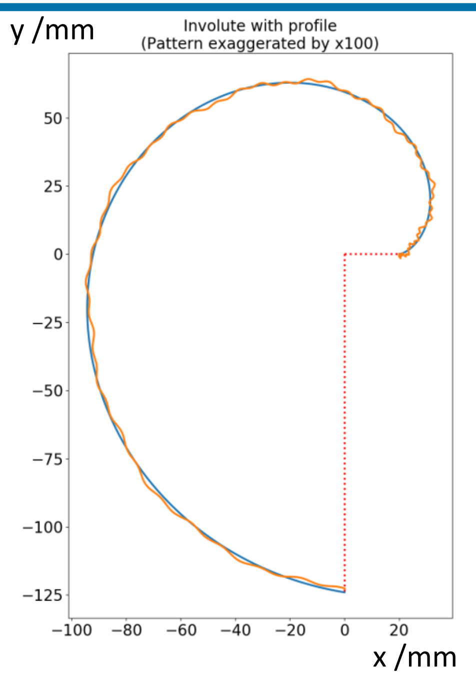
- **Hyperbolic Paraboloid**
  - Freeform test object for CMMs
  - Includes reference spheres for registration
  - Mathematically defined freeform surface
  - Surface is sampled in a regular grid (52 points)
  - Point by point comparison

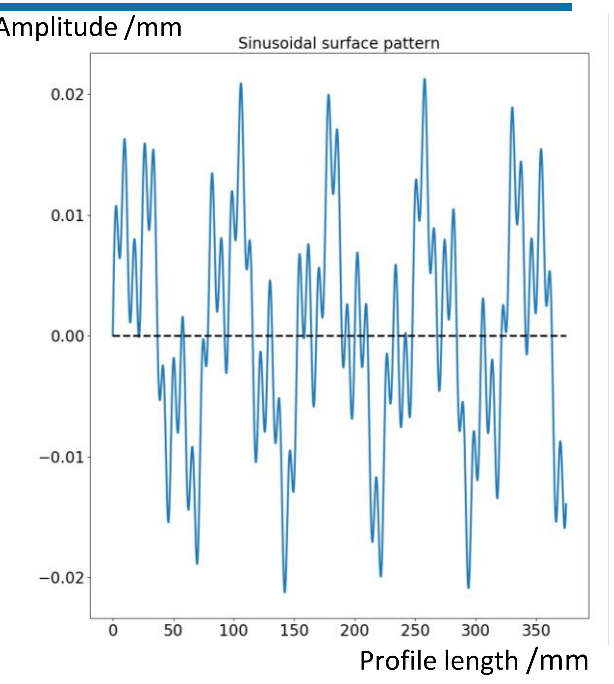




Hyperbolic paraboloid (100x100x60 mm) Source: CMI

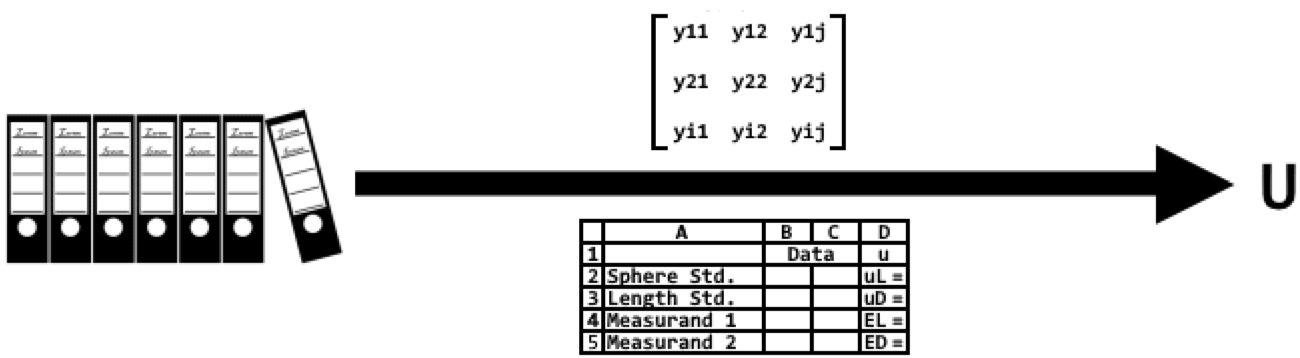
Reference standards: Freeform





- **Involute gear**
  - Gear measurement test object repurposed as a “simple” 1d freeform
  - Two versions:
    – Smooth involute
    – Involute with superimposed sinusoid

Part 3: Implementing the new methods



Implementation

- **Tool creation**
  - One template for each reference standard
    - Object-specific
    - Designed and tested by one participant
    - Same templates used by all participants

- **Tool sharing**
  - Avoids inconsistencies from implementation differences
    - Numerical differences between software kits
    - Programming errors and other human factors
  - Tools are designed for more accessibility
    - Understandable not just to the developer
    - Every consortium member needs to be able to use it
  - Common data input and results formats

Implementation: Method A

- **Excel spreadsheets (.xlsx)**
  - Data is pasted into the correct cells
    - Length and sphere standards
    - Repeat run and orientation results
  - Some additional settings controlled by cell entry
    - e.g., coverage factor, stylus type
  - Results displayed in the spreadsheet

- **Prime developer: CMI**
  - Includes a “manual” page
  - No expensive software licenses required
  - Very accessible to casual users
  - Easy to modify and adapt to new workpieces

Implementation: Method A

Reference data

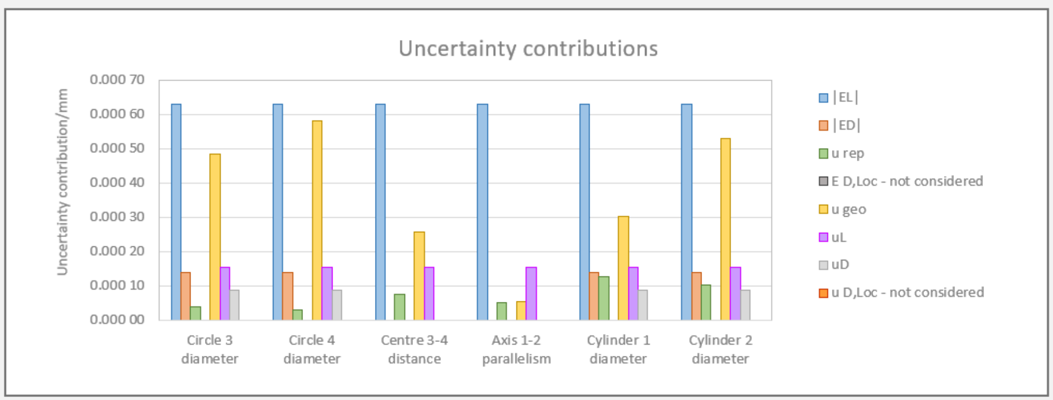
Measurement data

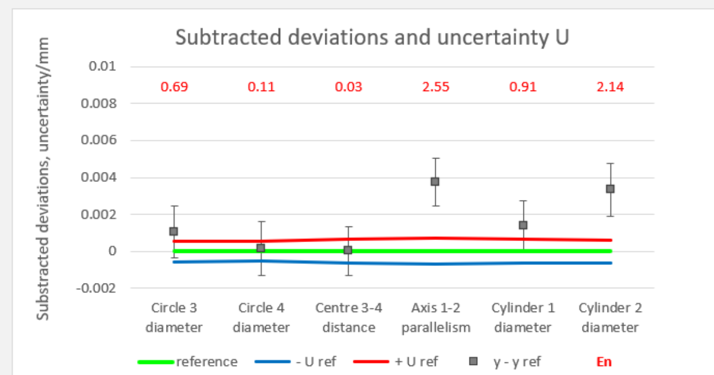
U_A

$E_{N,R}$

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	AE	AF	AG	AH
1	CONNECTING ROD MEASUREMENT																										
2	**Coverage factor k**	**2**	Cycle 1				Cycle 2				Cycle 3				Cycle 4				Cycle 5				**Measurement value**	**Expanded combined standard uncertainty**	**Calibrated value**	**Uncertainty of calibrated value**	**En number**
3	**Measured feature**		11 y	12 y	13 y	14 y	21 y	22 y	23 y	24 y	31 y	32 y	33 y	34 y	41 y	42 y	43 y	44 y	51 y	52 y	53 y	54 y	**y**	**U**	**y ref**	**U ref**	**En**
4	Circle 3 diameter	2.5.1	50.6079	50.6090	50.6082	50.6079	50.6080	50.6089	50.6082	50.6079	50.6079	50.6090	50.6083	50.6079	50.6079	50.6090	50.6083	50.6079	50.6079	50.6090	50.6083	50.6079	**50.608 26**	**0.001 42**	**50.607 21**	**0.000 55**	**0.69**
5	Circle 4 diameter	2.5.1	19.0152	19.0165	19.0153	19.0152	19.0152	19.0164	19.0153	19.0153	19.0153	19.0165	19.0152	19.0152	19.0152	19.0164	19.0153	19.0153	19.0153	19.0164	19.0152	19.0152	**19.015 54**	**0.001 46**	**19.015 38**	**0.000 52**	**0.11**
6	Centre 3 - Centre 4 distance	2.5.2	140.0067	140.0061	140.0068	140.0064	140.0068	140.0062	140.0068	140.0064	140.0068	140.0062	140.0066	140.0063	140.0066	140.0061	140.0066	140.0063	140.0066	140.0063	140.0066	140.0062	**140.006 46**	**0.001 32**	**140.006 42**	**0.000 64**	**0.03**
7	Axis 1 - Axis 2 parallelism	2.5.3	0.0055	0.0055	0.0056	0.0057	0.0055	0.0056	0.0056	0.0057	0.0055	0.0056	0.0055	0.0056	0.0054	0.0055	0.0055	0.0055	0.0055	0.0055	0.0055	0.0057	**0.005 56**	**0.001 30**	**0.001 79**	**0.000 70**	**2.55**
8	Cylinder 1 diameter	2.5.4	50.6127	50.6128	50.6121	50.6131	50.6126	50.6129	50.6124	50.6128	50.6126	50.6129	50.6124	50.6131	50.6125	50.6130	50.6123	50.6132	50.6126	50.6129	50.6125	50.6129	**50.612 71**	**0.001 37**	**50.611 33**	**0.000 65**	**0.91**
9	Cylinder 2 diameter	2.5.4	19.0284	19.0292	19.0280	19.0290	19.0285	19.0291	19.0279	19.0288	19.0285	19.0291	19.0278	19.0290	19.0284	19.0290	19.0278	19.0286	19.0286	19.0290	19.0277	19.0288	**19.028 56**	**0.001 44**	**19.025 22**	**0.000 62**	**2.14**

$$U = k\sqrt{E_L^2 + E_D^2 + E_{D,Loc}^2 + \frac{u_{rep}^2}{n_1} + \frac{u_{geo}^2}{n_2} + u_L^2 + u_D^2 + u_{D,Loc}^2}$$





Data input and results in the connecting rod template

Implementation: Method B

- **MatLab scripts**
  - Uses input templates similar to Method A workbooks
    - measured values
    - point clouds
    - vectors

- **Prime developer: NPL**
  - Uses MatLab due to matrix operations needed for evaluation
  - Adept users can adapt the code
    - E.g. translation into other languages

Implementation

- **Tools will be publicly available**

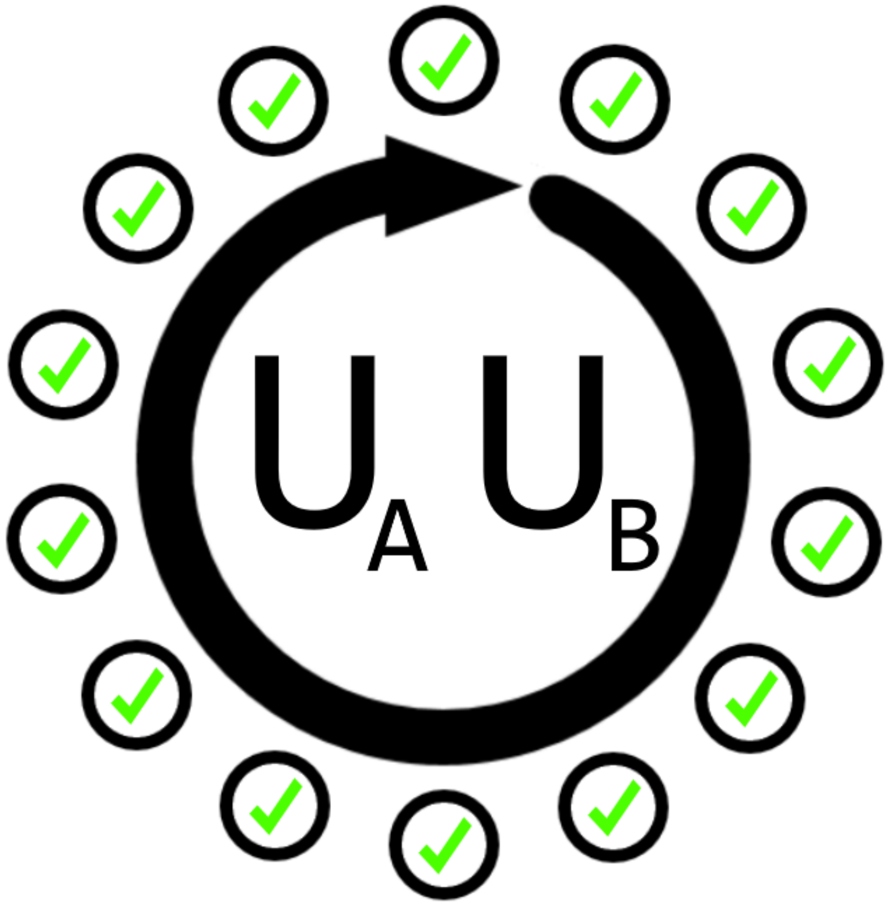
- **The original data will also be available**

- **ERGO:**
- **Users can adapt existing templates to new workpieces**
  - Easiest way to try out these methods
  - Build a template for your workpiece and compare to it other uncertainty estimates

- **Users can develop their own software**
  - Use the original tools and data as a reference
  - Compare your own results obtained from the same data

  → Validate your implementation

Part 4: Results



Results

- **All data sets were evaluated**
  - Results were collected and compared
  - In parts this is still on-going

- **Evaluated data:**
  - EUCoM method uncertainties U_A, U_B
  - Reference uncertainty U_{ref}
  - Reference uncertainty was based on established methods
  - Reference methods selected by the partners responsible for calibration

Proficiency testing

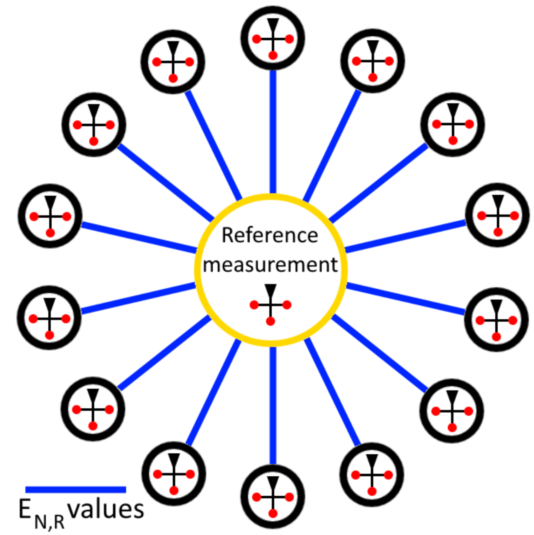
- **Use of proficiency testing for comparisons:**
  - Normalised Error (ISO 17043)
  - $E_N = \left| \frac{x_{meas} - x_{ref}}{\sqrt{U_{meas}^2 + U_{ref}^2}} \right|$
  - Pass-criterion: $E_N \leq 1$
  - Calculated for each measurand separately

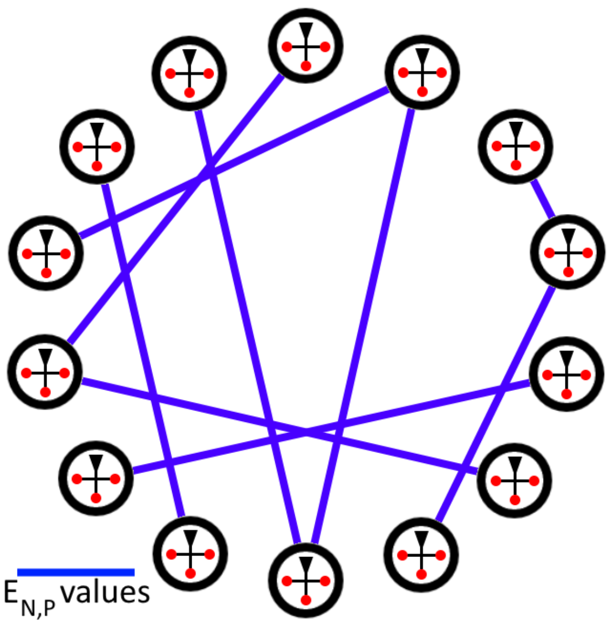
- **Limitations:**
  - Can‘t be used to spot overestimated U values
  - Measured values must be independent
  - Compared uncertainties must use the same confidence level
    – E.g. *k* = 2 or confidence-level 95%

Proficiency testing

- **Comparison to the reference value**
  - $E_{N,R}$

    calculated with either U_A or U_B and U_{ref}
  - Check conformity of EUCoM uncertainties with other methods

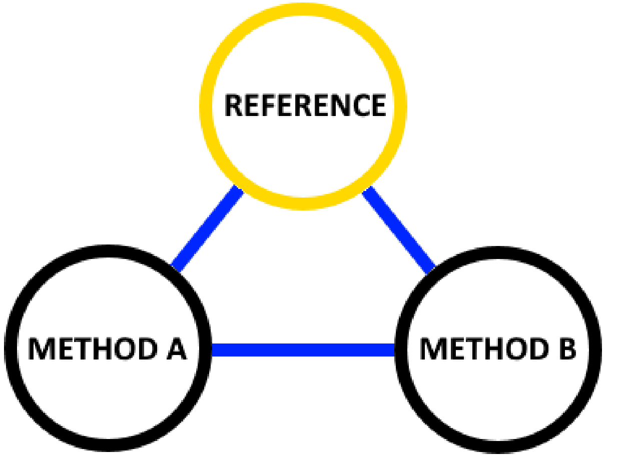




- **Comparison of paired values**
  - $E_{N,P}$
  - Pair up measurements and test them against each other
  - In effect: each partner provides reference values for the next
  - Check internal consistency of uncertainties – Method self-test

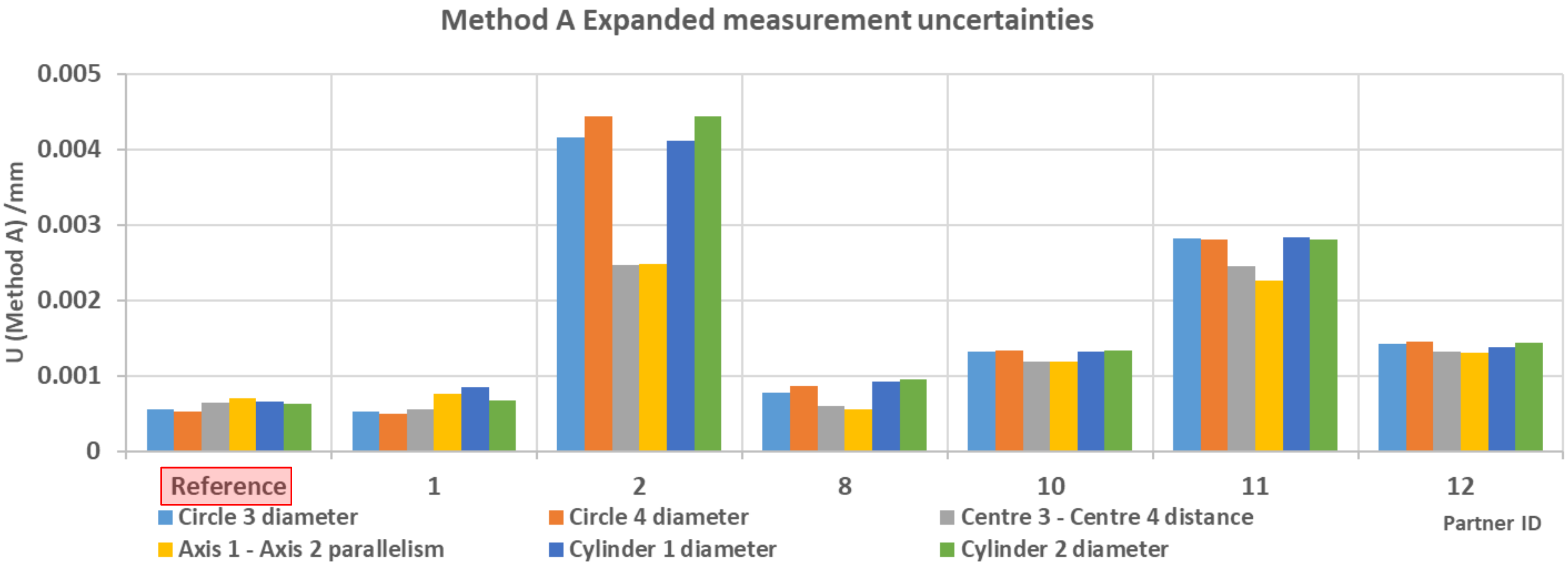
Proficiency testing

- **Method A vs. Method B**
  - Check whether the two estimates agree



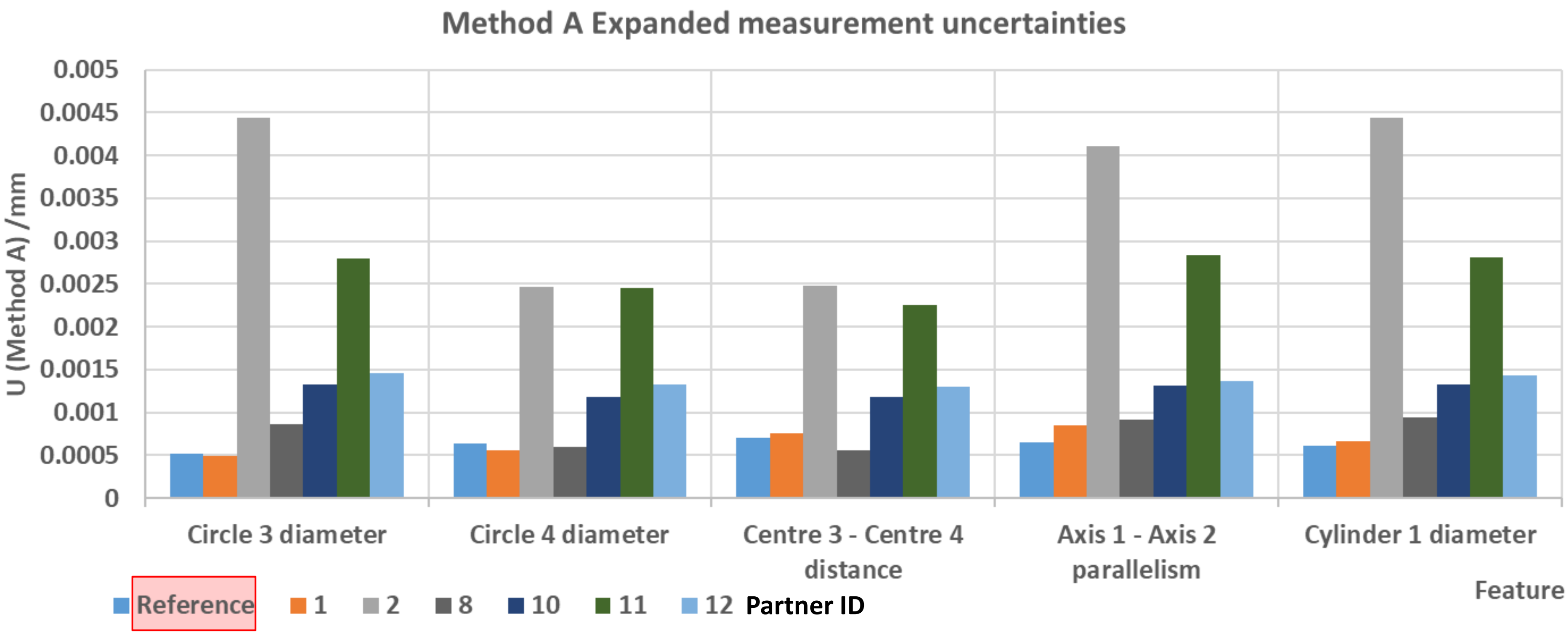
Results

- **Connecting rod, method A**
  - Noteworthy:
  - No obvious inconsistencies of U_A within each partner measurement
  - No obvious inconsistencies across the board
  - Some U_A are similar to U_{ref} (from VCMM)



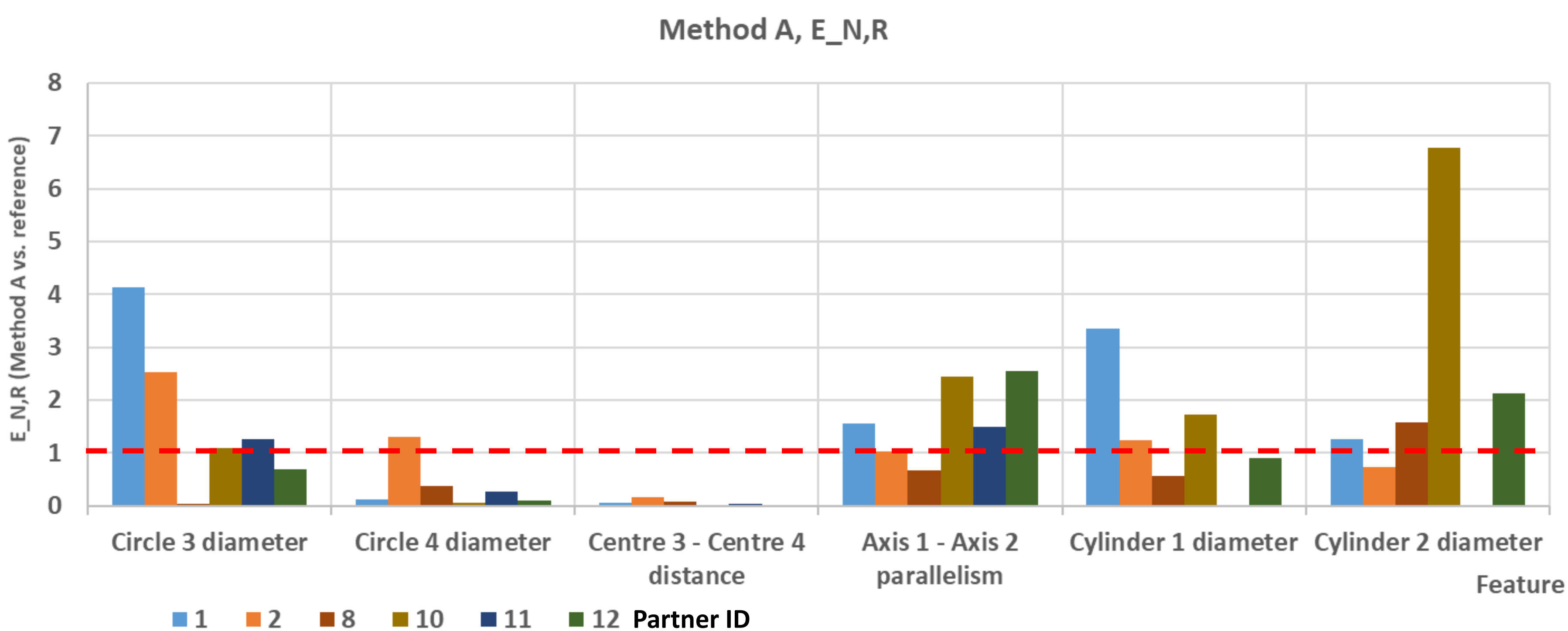
Results

- **Connecting rod, method A**
  - Same data, looking at features
  - Differences between measurements more visible – "Low quality" measurements were planned for
  - Also some very good results compared to U_{ref}



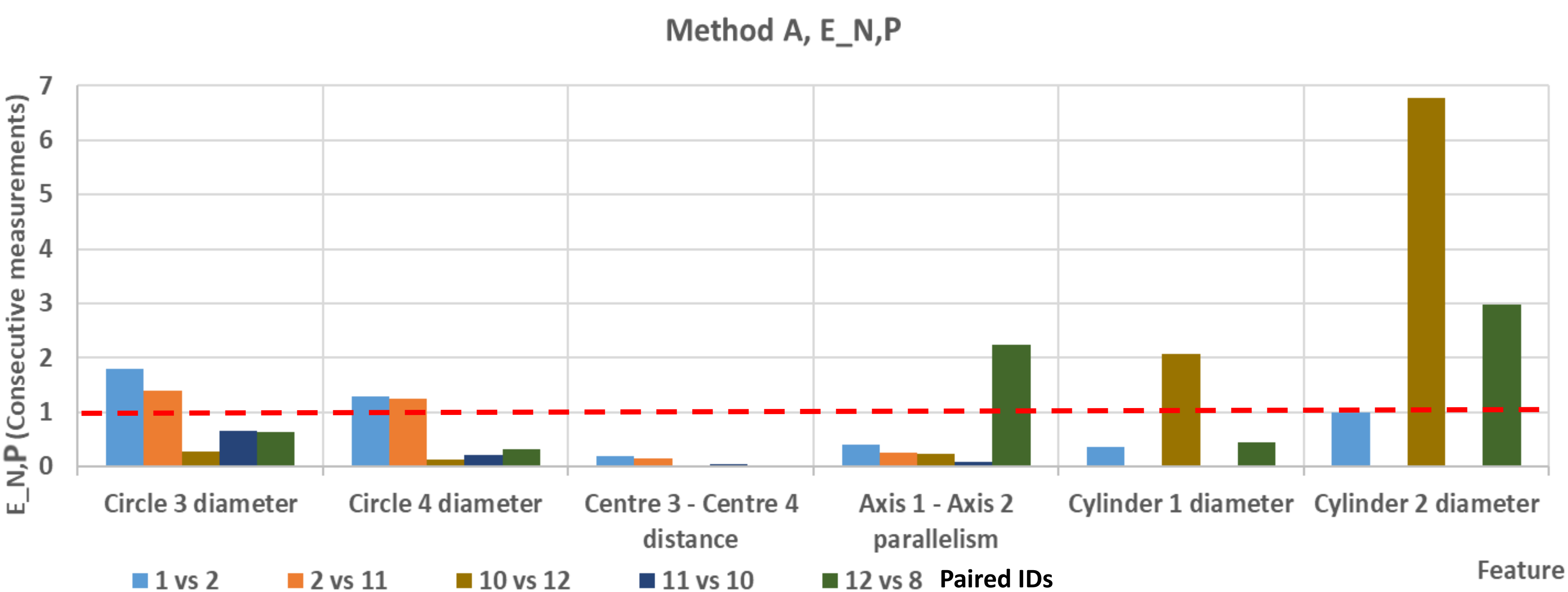
Results

- **Connecting rod, method A**
  - Normalised error based on the reference
  - Roughly half the population exceeds maximum



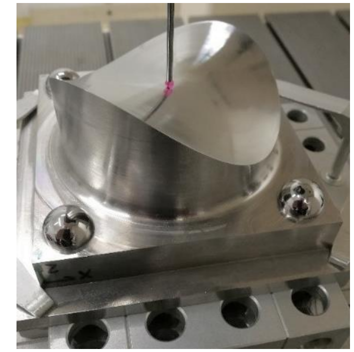
Results

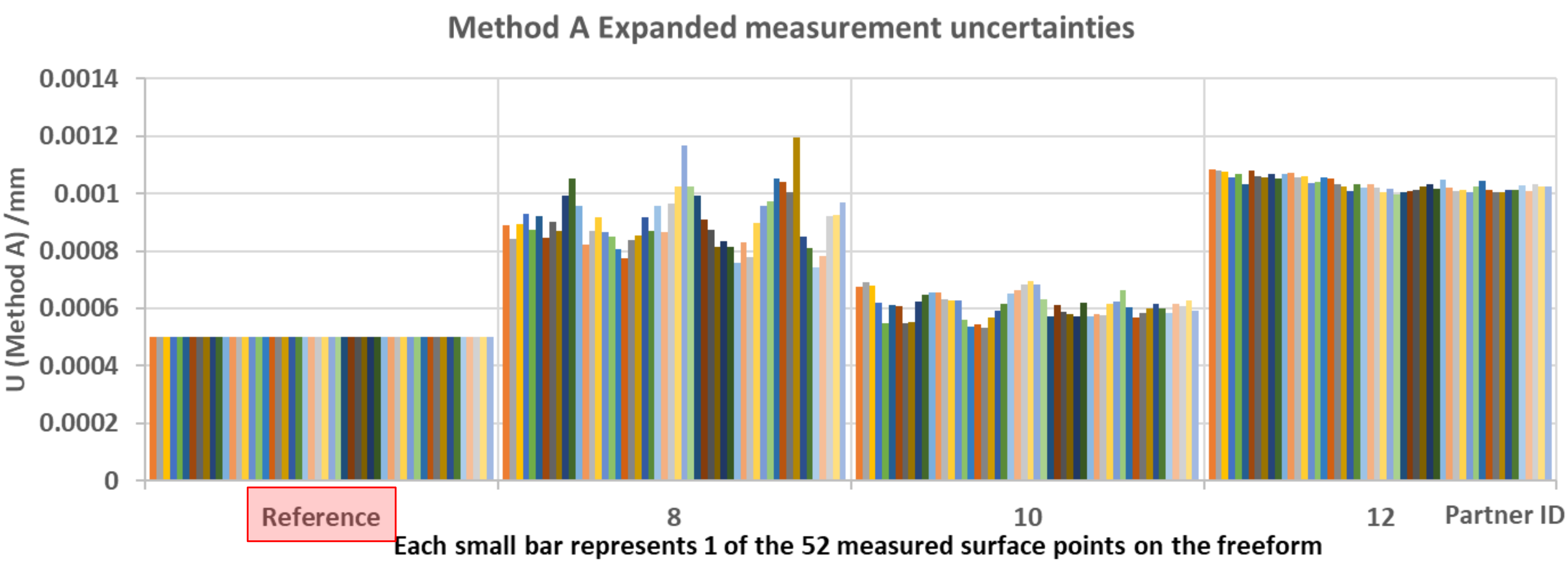
- **Connecting rod, method A**
  - Normalised error based on the reference
  - Again several limit violations
    - Possible issue with the artefact along the route
    - Reference re-verification or further analysis needed
    - Otherwise issue with Method A



Results

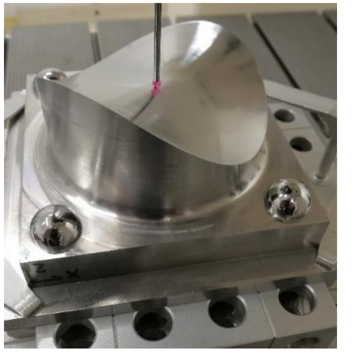
- **Hyperbolic paraboloid, method A**
  - Illustrates method A
    - Variability of U_A
    - Dominant contribution u_{geo} (probe)
  - U_A is the result of processing a lot of real measurement data
  - U_{ref} is a "traditional" estimate
    - Uses U_{max} for all points, hence constant

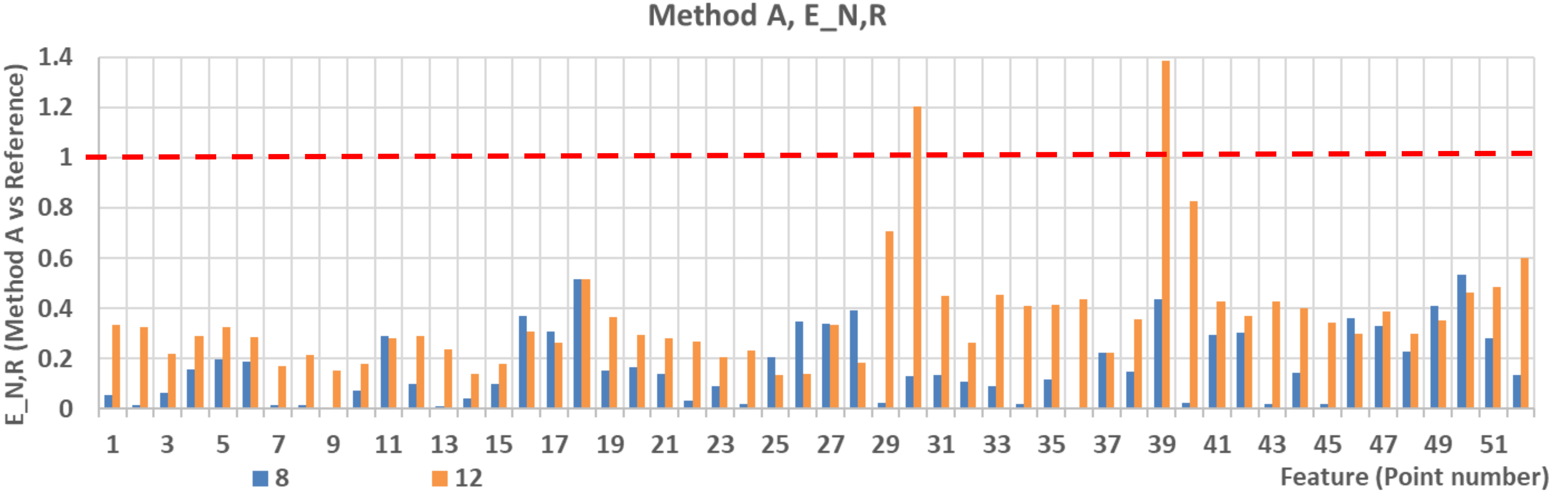




Results

- **Hyperbolic paraboloid, method A**
  - Preliminary result
    - Probable evaluation error in one data set (excluded from E_N chart)
    - Doesn't affect U_As
  - Otherwise low E_Ns, few violations
    - 2 / 104 values
    - Promising outcome (VCMM requires 95% agreement)





Results: Summary

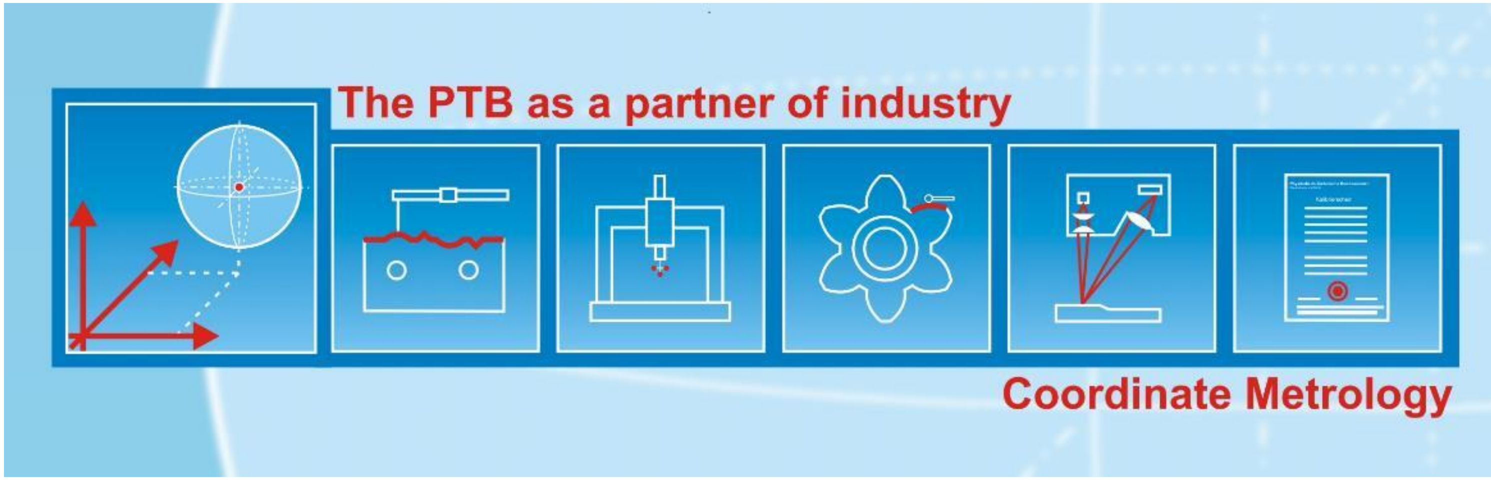
- **Method A results are ambiguous**
  - Can't say for certain whether it **does** or **does not** work, yet
- **In favour:**
  - Consistent U_A
    - U_As don't vary greatly within a single measurement
    - Little or no dependency on the feature being considered
    - Differences between measurements are to expected
    - As conditions change, so does U
      - Hardware, environment, …
  - Comparable uncertainties
    - By itself, U_A often agrees reasonably well with U_{ref}
- **Against:**
  - Proficiency testing says "no"…
    - A significant fraction of measurements fail the test
    - Not necessarily due to method A but it's hard to tell

Conclusion

- **EUCoM has created a generous data trove**
  - Different artefacts and measurands
- **EUCoM will provide the tools to apply the new uncertainty estimates**
  - The templates are a good starting point for customised software
- **Method validation still on-going/pending**
- **Method A is a practical approach to measurement uncertainty**
  - Feed it with a lot of measurement data to get an estimate
  - Avoids modelling and best-guess values
  - Modelling can be difficult
  - Some assumptions might be “uncomfortable”

Outlook

- **Results are still being added to the evaluation**
- **An analysis of method B will be added**
- **Intercomparison between new methods**
  - Method A vs. method B
- **Meta-analyses**
  - Usefulness of different orientations (Method A)
  - Identify key uncertainty contributors (u_{rep}, …)
  - Correlating method A results with CMM “accuracy” where possible
- **All tools and data will be made public**
  - Anonymous data (of course)
  - Ideal conditions for you to try out these methods yourself



Thank you for your attention!

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