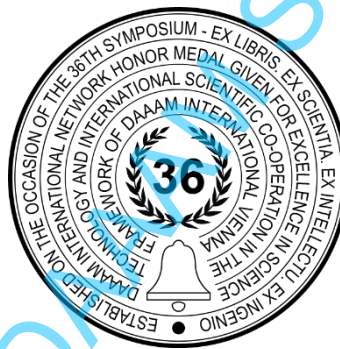


Influence of CMM Stylus Ball Diameter on the Evaluation of Internal Cylindrical Features

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Abstract

Coordinate measuring machines are widely used for dimensional and geometrical inspection, but their results depend on the probing strategy as well as machine accuracy. This study investigates the influence of stylus ball diameter on drilled internal cylindrical features. Six steel specimens with nominal hole diameters from 6.5 to 19.8 mm were evaluated using three ruby styli per specimen: a calculated size, a smaller size and a larger size. Measurements on a student CMM were compared with reference measurements from a higher-accuracy scanning CMM and a roundness measuring instrument. Diameter measurements were relatively insensitive to the investigated stylus-size changes, with maximum deviations from reference values within 5 %. Roundness and cylindricity were more sensitive to the measurement strategy. Sparse point sampling and differences in accessible measuring depth substantially affected form evaluation. The findings support selecting stylus geometry, qualification, point density, point distribution and measuring depth together. Further

experiments with identical axial ranges and increased point counts are needed to isolate the contribution of stylus diameter.

Keywords: coordinate measuring machine; stylus ball diameter; roundness; cylindricity; measurement strategy

1. Introduction

Coordinate measuring machines (CMMs) are among the most flexible instruments used for dimensional and geometrical verification in modern manufacturing. Their practical advantage lies in the ability to evaluate size, position and form characteristics within one measurement system. DAAAM research has repeatedly addressed the reliability and efficiency of CMM-based inspection. Stojkic et al. described CMMs as highly accurate and flexible contact measuring systems and compared their capabilities with optical 3D scanning [1]. Kubatova and Melichar demonstrated that the number of sampled points can significantly influence the evaluated element and recommended increasing the point count for form evaluation [2]. Melichar and Kubatova further showed, using a measurement-system-analysis approach, that stylus tip diameter can have a significant effect on overall measurement variability [3].

These findings are directly relevant to internal cylindrical features. Classical coordinate-metrology studies have also shown that the number and distribution of sampled points can materially change the evaluated circular feature [7], and that adaptive sampling can improve roundness assessment while reducing inspection effort [8]. A stylus must be small enough to enter the measured feature and reach the required locations, but its diameter also determines the mechanical filtering of local surface irregularities and the practical accessibility of the feature. A very small stylus can respond to local surface texture and drilling marks, whereas an excessively large stylus may limit accessibility or produce an unfavourable contact geometry. At the same time, form characteristics such as roundness and cylindricity depend strongly on the number and distribution of acquired points. The influence of stylus size therefore cannot be evaluated independently from the sampling strategy. More general sampling-strategy research likewise confirms that sample size, point distribution, workpiece size and surface characteristics interact in form-error evaluation [9], [10].

The objective of this study is to quantify the influence of stylus ball diameter on the measured diameter, roundness and cylindricity of drilled holes and to distinguish this influence from limitations caused by the number of points and measuring depth. The experimental data originate from the author's earlier bachelor thesis focused on the analysis of shape-element measurement on a 3D measuring machine [5]. The present paper reformulates the experiment as a compact metrological study and relates its conclusions to previous DAAAM work in coordinate metrology.

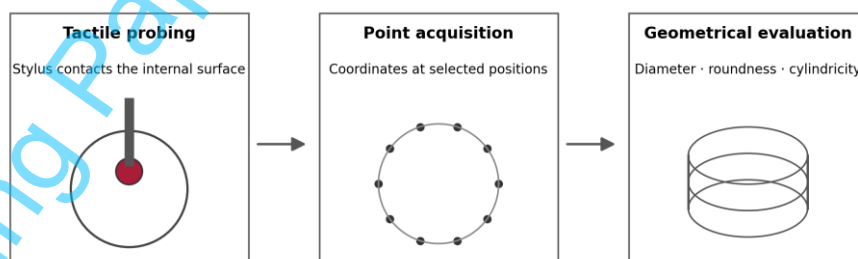


Fig. 1. Principle of tactile CMM measurement and evaluation of an internal cylindrical feature.

2. Background and Related DAAAM Research

Contact CMM measurement is based on acquiring coordinates of points on the surface of the inspected component and fitting an ideal geometrical element to those points. Consequently, the resulting value depends on the machine, probe system, stylus, qualification procedure, environmental conditions, point distribution and evaluation algorithm. The DAAAM literature provides several studies that are especially relevant to the present experiment.

Kubatova and Melichar investigated the influence of the number of points used to construct circles and cylinders on a CMM [2]. Their experiment used calibration rings and a ruby stylus and showed that a low point count can be insufficient for stable evaluation. They concluded that at least 15 points should be used for circularity and ring diameter and at least 30 points for cylindricity and cylinder diameter under their test conditions. This is important for the present study because the student CMM measurements used ten points per circular section; therefore, some differences attributed to stylus size may actually be amplified by sparse sampling.

Melichar and Kubatova examined CMM stylus evaluation by reverse application of measurement system analysis [3]. Their results identified stylus tip diameter as a parameter with a significant influence on measurement variability. The study supports treating the stylus as an active part of the measurement chain rather than a neutral accessory. More recently, Blabol and Kutlwaser investigated repeated changes of the sensing system and their influence on measurement accuracy [4], confirming the broader importance of probe-system configuration and qualification for reliable CMM inspection.

DAAAM publications also show the value of using high-accuracy CMM measurements as reference data. Hrusecky et al. used a ZEISS Prismo Ultra CMM under laboratory conditions and repeated measurements ten times to obtain reference values in a study comparing CMM and computed tomography [6]. This approach is conceptually similar to the present work, where a more accurate scanning CMM and a dedicated roundness instrument were used as reference systems for the student CMM.

3. Materials and Methods

3.1. Test specimens and measured characteristics

Six steel specimens containing drilled blind holes were selected. The nominal hole diameters were 6.5, 8.5, 10.5, 13, 16 and 19.8 mm. Drilled holes were intentionally used because their real surfaces contain form deviations that allow differences between probing strategies to become visible. The investigated characteristics were internal diameter, roundness and cylindricity. Measurements were performed at several depths so that local changes along the hole could also be observed.



Fig. 2. Schematic representation of a straight spherical CMM stylus with a ruby ball, based on the ZEISS standard stylus design [17].

Hole diameter [mm]	Smaller stylus [mm]	Calculated stylus [mm]	Larger stylus [mm]
6.5	1.0	1.5	2.0
8.5	1.5	2.0	3.0
10.5	1.5	2.0	3.0
13	2.0	3.0	5.0
16	2.0	3.0	5.0
19.8	3.0	5.0	8.0

Table 1. Stylus ball diameters used for the student CMM measurements

3.2. Reference measurement systems

Roundness and cylindricity reference values were obtained using a dedicated roundness measuring instrument. The roundness instrument used a 1.5 mm ruby tip, five cross-sections and a high point density of approximately 10,000 points per section. A higher-accuracy scanning CMM was used primarily as the reference for diameter and as an additional comparison for form characteristics. Its specified maximum permissible length error was $0.9 + L/350 \mu\text{m}$, and a 1.5 mm stylus was used. The scanning mode allowed hundreds of points to be acquired while maintaining continuous contact with the surface.

The student CMM used a contact probing system with ruby styli. For each hole, the calculated stylus size was complemented by one smaller and one larger stylus, as shown in Table 1. Before measurement, all styli were qualified using a calibration sphere. The measurement programs were prepared in ZEISS CALYPSO 2021. Ten points were used for each circular section. Three sections were measured at different depths, and each measurement was repeated five times. The five repetitions were subsequently averaged.



Fig. 3. Student coordinate measuring machine used for the experiment [5].



Fig. 4. Stylus qualification on the calibration sphere before measurement [5].

3.3. Evaluation procedure

For diameter, the scanning CMM result was treated as the reference value. For roundness and cylindricity, the roundness measuring instrument was treated as the primary reference. Relative deviation was calculated as the difference between the investigated result and the reference result divided by the reference result. For form characteristics, percentage deviations can become numerically large because the reference values themselves are small; therefore, both absolute values and percentage deviations were considered when interpreting the results.

4. Results

4.1. Diameter

The diameter results were the most stable part of the experiment. Across all six specimens, changing from the calculated stylus to the selected smaller or larger stylus produced only small changes in the evaluated diameter. The maximum deviation from the reference value remained within 5 % for all three stylus categories. This indicates that, within the investigated range and for the tested drilled holes, stylus ball diameter was not the dominant factor for diameter evaluation.

For the 19.8 mm specimen, the averaged student-CMM diameter obtained with the 8 mm stylus was 19.8306 mm at 5 mm depth, 19.8294 mm at 12 mm depth and 19.8260 mm at 17 mm depth. The corresponding scanning-CMM values were approximately 19.836 mm, 19.833 mm and 19.824 mm. The differences are small in relation to the nominal dimension and illustrate the general trend observed for all specimens.

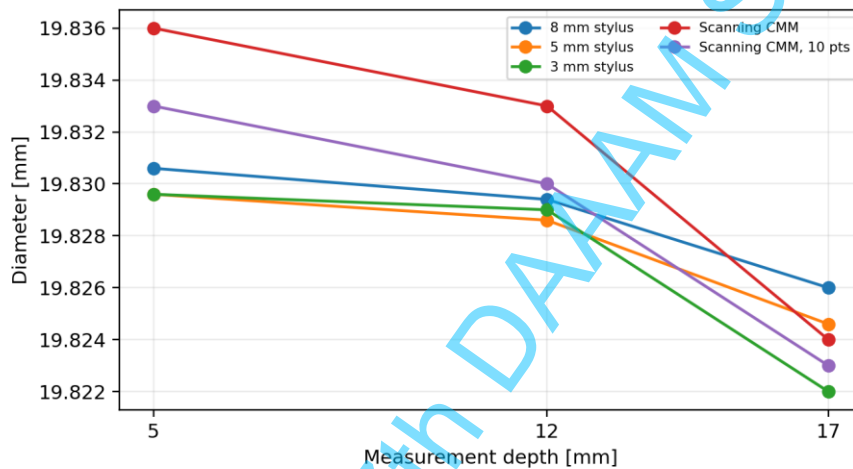


Fig. 5. Diameter of specimen D19.8 at three measuring depths. Graph generated from the experimental data reported in [5].

4.2. Roundness

Roundness was substantially more sensitive than diameter. The deviations varied with both stylus size and measuring depth. For most specimens, the difference between the largest and smallest stylus became smaller at greater measuring depths, while the shallowest sections showed the largest discrepancies. The beginning of a drilled hole is affected by tool entry and may contain stronger local form errors, which makes sparse point sampling especially sensitive to the exact contact locations.

The largest percentage deviations in the complete comparison exceeded 100 %. For the calculated stylus, the maximum reported deviation relative to the ten-point scanning-CMM comparison was approximately -145 %, compared with about -125 % for the smallest stylus and -130 % for the largest stylus. These values should not be interpreted as a pure stylus-diameter effect. The ten-point strategy, local drilling irregularities and the different measuring depths all contribute to the result. This interpretation agrees with the DAAAM study of Kubatova and Melichar [2], which showed that form evaluation requires a considerably denser point set than the mathematical minimum.

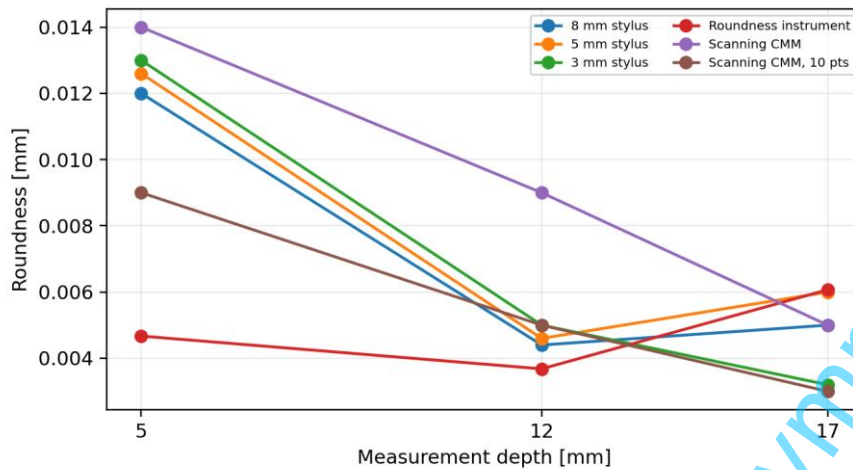


Fig. 6. Roundness of specimen D19.8 at three measuring depths. Graph generated from the experimental data reported in [5].

4.3. Cylindricity

Cylindricity produced the largest differences between measurement systems. The main limitation was the accessible measuring depth of the student CMM with the available styli. The roundness instrument and scanning CMM could evaluate a larger portion of the drilled hole, whereas the student CMM could not always reach the same axial range. Consequently, the fitted cylinder was constructed from different portions of the real surface.

Method / stylus	D19.8	D16	D13	D10.5	D8.5	D6.5
Scanning CMM	0.072	0.04	0.05	0.017	0.086	0.075
Largest stylus	0.0122	0.0092	0.0216	0.009	0.031	0.0086
Calculated stylus	0.013	0.0098	0.0218	0.009	0.031	0.0086
Smallest stylus	0.0158	0.009	0.0218	0.0092	0.0308	0.009
Roundness instrument	0.05145	0.0193	0.03949	0.0169	0.08507	0.07699
Scanning CMM, 10 pts	0.057	0.03	0.043	0.012	0.078	0.069

Table 2. Cylindricity results for the six specimens (values in mm)

Table 2 shows that the three student-CMM stylus results are relatively close to one another, but all can differ strongly from the reference systems. For five of the six specimens, the difference between the individual student-CMM styli was within approximately 5 %; for the 19.8 mm specimen it was within approximately 7 %. However, the maximum deviation relative to the ten-point scanning-CMM values reached about 87.5 %. This demonstrates that the accessible axial range and sampling strategy had a stronger effect on cylindricity than the stylus-diameter change alone.

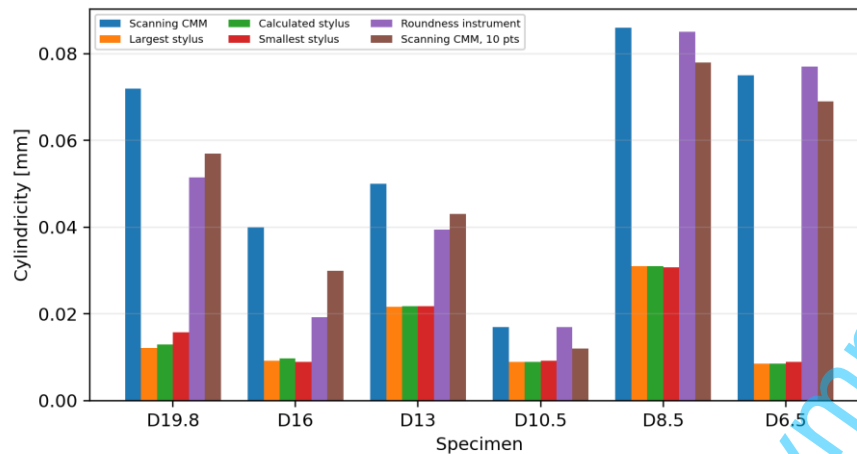


Fig. 7. Comparison of cylindricity values for all six specimens and measurement strategies. Graph generated from the experimental data reported in [5].

5. Discussion

The main findings are summarized in Table 3. The comparison shows a clear difference between dimensional and form characteristics. Hole diameter remained comparatively stable when the stylus ball diameter was changed, whereas roundness and cylindricity were much more sensitive to the complete measurement strategy.

For roundness, the ten-point discrete strategy can undersample local peaks and valleys. The large deviations observed here are therefore consistent with earlier work showing that point density and distribution materially influence form evaluation [2], [7], [8], [9], [10]. The results should not be interpreted as an effect of stylus diameter alone.

Cylindricity was dominated by another limitation: the compared systems did not always cover the same axial length of the hole. The maximum deviation of about 87.5% relative to the ten-point scanning-CMM comparison is consequently better interpreted as a combined effect of accessible depth, sampling range and evaluation strategy [14] than as evidence of an unsuitable stylus diameter.

To address this limitation, future experiments will apply identical axial measurement coverage to the student CMM, the higher-accuracy scanning CMM and the dedicated roundness instrument. The same axial start and end positions and comparable section locations will be used for each specimen, with stylus accessibility verified before measurement. This controlled design will prevent differences in evaluated cylinder length from being conflated with stylus-size effects and will allow the mechanical filtering associated with stylus ball diameter to be assessed separately from accessibility constraints. Point density and distribution will also be standardized or varied systematically to distinguish sampling effects from the influence of stylus geometry.

Overall, the experiment supports treating the probe as part of a complete measurement plan. Stylus size, qualification, point count, point distribution and accessible depth should be specified together, which is consistent with previous DAAAM studies on stylus-related variability and sensing-system configuration [3], [4] and with broader CMM verification research [11], [12], [13], [14], [15], [16].

Evaluated aspect	Experimental evidence	Main interpretation	Relation to literature
Diameter	Maximum deviation from the reference remained within 5% for all three stylus-size groups.	Moderate changes of ball diameter had only a limited effect on the fitted hole diameter after correct qualification.	Consistent with the need to control probe configuration and effective stylus diameter [3], [11], [12], [13].
Roundness	Maximum reported deviations exceeded 100%; the calculated-stylus case reached approximately -145% in the comparison used.	Form evaluation is much more sensitive to sparse sampling and local surface irregularities than diameter evaluation.	Supports the point-density findings reported by Kubatova and Melichar [2] and general sampling studies [7], [8], [9], [10].
Cylindricity	Student-CMM stylus results were generally close to each other, while deviation from the ten-point scanning-CMM reference reached about 87.5%.	Accessible depth and axial sampling range dominated the comparison; systems covering different depths do not evaluate the same geometrical population.	Agrees with cylindricity sampling research showing combined effects of distribution, algorithm and point count [14].
Measurement strategy	Ten-point discrete probing, different stylus diameters and limited hole accessibility were combined in the student-CMM experiment.	Stylus diameter should not be specified alone; qualification, point count, point distribution and measuring depth must be defined together.	Compatible with DAAAM work on stylus/MSA and sensing-system configuration [3], [4] and statistical CMM verification [15], [16].

Table 3. Synthesis of the main experimental findings and their interpretation

6. Practical Recommendations

For dimensional inspection of drilled internal features similar to those investigated here, the stylus should first be selected to guarantee safe accessibility and adequate stiffness. A ball diameter close to the calculated value is preferable, but a moderately smaller or larger stylus can still provide comparable diameter results when correctly qualified. For roundness, the point count should be increased beyond the ten-point strategy used in this experiment whenever the required tolerance is tight or the surface contains machining marks. For cylindricity, several sufficiently separated cross-sections should cover the same axial range for all compared measurement systems. If the stylus cannot reach the required depth, the result should not be treated as directly comparable with a full-depth reference measurement.

7. Conclusion

The influence of CMM stylus ball diameter was investigated using six drilled steel specimens and three stylus sizes for each hole. The results confirm that the effect of stylus diameter depends strongly on the evaluated characteristic. Diameter measurements were relatively insensitive to the investigated stylus-size changes and remained within 5 % of the reference values. Roundness showed much larger deviations, which were influenced by stylus size, measuring depth and especially sparse point sampling. Cylindricity showed the largest discrepancies between systems, with maximum deviations approaching 87.5 % in the comparison with a ten-point scanning-CMM dataset; however, this was mainly caused by different accessible measuring depths and sampling conditions.

The main practical conclusion is that stylus diameter should not be optimized in isolation. Reliable CMM inspection of internal cylindrical features requires a combined selection of stylus geometry, point density, point distribution and measuring depth. Future work should repeat the experiment with identical axial ranges on all systems and with systematically increased point counts so that the independent contribution of stylus diameter can be quantified more precisely.

8. References

- [1] Stojkic, Z.; Culjak, E. & Saravanja, L. (2020). 3D Measurement - Comparison of CMM and 3D Scanner, Proceedings of the 31st DAAAM International Symposium, pp.0780-0787, B. Katalinic (Ed.), DAAAM International, Vienna, Austria. DOI: 10.2507/31st.daaam.proceedings.108.

- [2] Kubatova, D. & Melichar, M. (2019). Influence of the Number of Points on the Evaluated Element when Measuring on CMM, Proceedings of the 30th DAAAM International Symposium, pp.0476-0483, B. Katalinic (Ed.), DAAAM International, Vienna, Austria. DOI: 10.2507/30th.daaam.proceedings.064.
- [3] Melichar, M. & Kubatova, D. (2019). Reverse Application of MSA Tool for CMM Stylus Evaluation, Proceedings of the 30th DAAAM International Symposium, B. Katalinic (Ed.), DAAAM International, Vienna, Austria. DOI: 10.2507/30th.daaam.proceedings.053.
- [4] Blabol, V. & Kutlwaser, J. (2025). The Impact of Changing the Sensing System on Measurement Accuracy, Proceedings of the 36th DAAAM International Symposium, pp.0285-0292, B. Katalinic (Ed.), DAAAM International, Vienna, Austria. DOI: 10.2507/36th.daaam.proceedings.040.
- [5] Čása, J. (2023). Analysis of the Process of Measuring Shape Elements on a 3D Measuring Machine. Bachelor Thesis, University of West Bohemia, Faculty of Mechanical Engineering, Department of Machining Technology, Pilsen, Czech Republic.
- [6] Hrusicky, R.; Molnar, I.; Gorog, A. & Michal, D. (2019). Influence of Computed Tomography Detector Resolution on Measured Values of Shape and Dimensional Accuracy, Proceedings of the 30th DAAAM International Symposium, B. Katalinic (Ed.), DAAAM International, Vienna, Austria. DOI: 10.2507/30th.daaam.proceedings.095.
- [7] Chan, F.M.M.; King, T.G. & Stout, K.J. (1996). The influence of sampling strategy on a circular feature in coordinate measurements. *Measurement*, 19(2), 73-81. DOI: 10.1016/S0263-2241(96)00067-X.
- [8] Rossi, A. (2001). A form of deviation-based method for coordinate measuring machine sampling optimization in an assessment of roundness. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 215(11), 1505-1518. DOI: 10.1243/0954405011519411.
- [9] Mian, S.H.; Al-Ahmari, A.M. & Alkhalefah, H. (2019). Analysis and Realization of Sampling Strategy in Coordinate Metrology. *Mathematical Problems in Engineering*, 2019, 9574153. DOI: 10.1155/2019/9574153.
- [10] Colosimo, B.M.; Gutierrez, E.; Moroni, G. & Petrò, S. (2008). Statistical Sampling Strategies for Geometric Tolerance Inspection by CMM. *Economic Quality Control*, 23(1), 109-121. DOI: 10.1515/EQC.2008.109.
- [11] Muralikrishnan, B.; Stone, J.A. & Stoup, J.R. (2011). Effective stylus diameter determination using near zero-width reference. *Precision Engineering*, 35(3), 500-504. DOI: 10.1016/j.precisioneng.2011.02.003.
- [12] Measurement of form error of a probe tip ball for coordinate measuring machine (CMM) using a rotating reference sphere (2020). *Precision Engineering. Study of probe-tip ball form error, diameter and calibration uncertainty*.
- [13] Novel CMM-based implementation of the multi-step method for the separation of machine and probe errors (2011). *Precision Engineering. Study addressing separation of CMM machine errors and probing-system errors for different stylus lengths*.
- [14] Mian, S.H. et al. (2020). Prognosis and Multiobjective Optimization of the Sampling Plan for Cylindricity Evaluation. *Mathematical Problems in Engineering*, 2020, 8201312. DOI: 10.1155/2020/8201312.
- [15] On the selection of flatness measurement points in coordinate measuring machine inspection (2000). *International Journal of Machine Tools and Manufacture*, 40(3), 427-443. DOI: 10.1016/S0890-6955(99)00059-0.
- [16] Petrò, S. & Moroni, G. (2021). A statistical point of view on the ISO 10360 series of standards for coordinate measuring systems verification. *Measurement. Study discussing statistical aspects of CMM verification and single-stylus probing performance*.

- [17] Carl Zeiss Industrielle Messtechnik GmbH. ZEISS Styli: Measuring probes for coordinate measuring machines; standard spherical styli and ruby probe balls. ZEISS Industrial Quality Solutions, Oberkochen, Germany, accessed 1 September 2026.

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