COMPARATIVE PERFORMANCE BETWEEN TWO PHOTOGRAMMETRIC SYSTEMS AND A REFERENCE LASER TRACKER NETWORK FOR LARGE-VOLUME INDUSTRIAL MEASUREMENT

OLIVER C. MARTIN (o.c.martin@bath.ac.uk)
JODY E. MUELANER (j.e.muelaner@bath.ac.uk)
VIMAL DHOKIA (v.dhokia@bath.ac.uk)
The University of Bath, Bath, UK
STUART ROBSON (s.robson@ucl.ac.uk)
University College London, London, UK
AMIR KAYANI1 (amir.kayani@npl.co.uk)
National Physical Laboratory, Teddington, UK
PAUL. G. MAROPOULOS2 (p.g.maropoulos@aston.ac.uk)
Aston University, Birmingham, UK

1Previously at Airbus UK Limited, Bristol, UK
2Previously at The University of Bath, Bath, UK

Abstract

This paper determines the capability of two photogrammetric systems in terms of their measurement uncertainty in an industrial context. The first system – V-STARS inca3 from Geodetic Systems Inc. – is a commercially available measurement solution. The second system comprises an off-the-shelf Nikon D700 digital camera fitted with a 28 mm Nikkor lens and the research-based Vision Measurement Software (VMS). The uncertainty estimate of these two systems is determined with reference to a calibrated constellation of points determined by a Leica AT401 laser tracker. The calibrated points have an average associated standard uncertainty of 12.4 μm, spanning a maximum distance of approximately 14.5 m. Subsequently, the two systems’ uncertainty was determined. V-STARS inca3 had an estimated standard uncertainty of 43.1 μm, thus outperforming its manufacturer’s specification; the D700/VMS combination achieved a standard uncertainty of 187 μm.

KEYWORDS: coordinate comparison, laser tracker, photogrammetry, uncertainty, V-STARS
**INTRODUCTION**

Laser trackers are used extensively for large-scale industrial and scientific metrology (Peggs et al., 2009). The aerospace sector utilises laser tracker systems for the setting and conformance tasks required for wing-level manufacture, in particular jigs and fixtures. In part, this is due to the dynamic measurement capability of laser trackers. However, many static point measurements are required in these applications and photogrammetry is often overlooked as a potential alternative. Photogrammetric systems hold many advantages over laser trackers including:

1. simultaneous multiple-target measurement;
2. quick measurement time;
3. lower operator skill level; and
4. inexpensive measurement targets.

These benefits are offset by the systems’ accuracy and cost. The cost is comparable to the laser tracker; however, the accuracy is invariably considered to be not as good as a laser tracker even though, in certain operating environments, comparable accuracy levels are attained. As computational costs reduce, and readily available digital cameras rise in standard – in terms of mechanical construction, sensors and lenses – photogrammetry could provide a far more cost-effective alternative to laser tracker measurement systems.

This work compares the capability of two imaging systems:

1. the V-STARS INCA3 from Geodetic Systems Inc. (GSI); and
2. a Nikon D700 digital single-lens reflex (DSLR) camera fitted with a 28 mm Nikkor lens and using Vision Measurement Software (VMS).

The V-STARS system is representative of a commercial photogrammetric system built around a custom-designed imaging system and software. In contrast, the second system utilises an off-the-shelf 12 Mpixel digital camera and lens in combination with research-based photogrammetric software, and costing an order of magnitude less than the commercial system. Manufacturers state an instrument’s performance in terms of measurement uncertainty; however, this is often assessed and determined in a controlled environment and in accordance with VDI-Standard (2002) industrial engineering standards, and not in the intended industrial setting. Consequently, an independent verification of a measurement system’s capability in an environment similar to that of the intended application environment is required to achieve confidence in an instrument’s performance; especially for tolerance-critical operations, such as those found in the aerospace sector. The uncertainty of measurement for each system in an industrial environment typical of aerospace manufacture is an output of the current study. The measurement uncertainty is determined by using a method of coordinate comparison. The reference network provides a coordinate definition (determination of the parameters defining the X, Y, Z system used) with a known measurement uncertainty, improving on the use of a single laser tracker as a reference standard (Summan et al., 2015).

The uncertainty estimates for the two photogrammetric systems are compared to a single-station laser tracker measurement, utilised in manufacturing applications, as a performance benchmark.

**METHODOLOGY**

The evaluation will determine the measurement uncertainty of static measurements in an environment and volume similar to the intended industrial application, that is, the
conformance measurement of wing-level tooling structures within aircraft manufacture. The estimated measurement uncertainty is determined by using a method of coordinate comparison: comparing the measured coordinates with a reference network possessing a quantified associated uncertainty (Muelaner et al., 2009; Hughes et al., 2010). A reference network of discrete points will be established with an accurately determined coordinate definition. In turn, the photogrammetric systems will remeasure the reference network. Subsequently, the total uncertainty of measurement will be determined by constructing an uncertainty estimate in accordance with the Guide to the Expression of Uncertainty in Measurement (ISO/IEC, 2008).

**Uncertainty Terminology**

The following terms are used throughout this uncertainty evaluation and are defined by ISO/IEC (2007, 2008):

- **Measurand.** \( Y \): description of the quantity to be measured.
- **Uncertainty.** A parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand \( Y \), where \( Y = f(X_1, X_2, \ldots, X_N) \). (Note \( Y \) and \( X \) are used for measurands and input; lower case \( x \) and \( y \) for their estimates.)
- **Standard uncertainty.** \( u(x) \): uncertainty of a measurement expressed as a standard deviation.
- **Combined standard uncertainty.** \( u_c(y) \): standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities. Equal to the positive square root of a sum of terms, the terms being the variances or covariance of these other quantities weighted according to how the measurement result varies with changes in these quantities. In the case of independent input quantities, the combined standard uncertainty is given by

\[
    u_c^2(y) = \sum_{i=1}^{n} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i). 
\]

- **Sensitivity coefficient.** \( c_i \): describes how the output estimate \( y \) varies with changes in the values of the input estimates \( x_1, x_2, \ldots, x_N \), such that:

\[
    c_i = \frac{\partial f}{\partial x_i}. 
\]

- **Coverage factor.** \( k \): numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty (\( k > 1 \)).
- **Expanded uncertainty.** \( U = ku_c(y) \): quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

**Reference Network**

The reference network in this work is a constellation of 11 points within an approximate volume of 13.5 m × 8 m × 3 m (with a maximum point-to-point distance of 14.5 m), accurately measured using a Leica AT401 laser tracker. Each of the 11 points...
within the reference network was measured nine times from different laser tracker positions (Fig. 1). The coordinate definitions from each measurement location are combined using a weighted least-squares regression, with the intention of minimising the associated point uncertainty based on the instruments’ uncertainty characteristics (Muelaner et al., 2010). The weighted network adjustment is, in turn, based on the three main components of the laser tracker uncertainty model, namely, the two angular encoders and radial distance measurement. Subsequently, the uncertainty associated with each point was computed via a Monte Carlo simulation (MCS). The constellation of points was computed with an average magnitude uncertainty, \( u(n_m) \), of 11.8 \( \mu m \) at \( k = 1 \) (a confidence interval of 68.26%). This analysis was carried out with SpatialAnalyzer software.

Measurement errors attributable to variations in the refractive index and temperature during the data acquisition have not been explicitly compensated in the network adjustment. As a result, any errors arising from these sources will be seen in the network residuals and internal correlations between measurements and parameters. The computed uncertainty includes a number of uncertainty contributions, including the instrument parameters in ranging and angular uncertainty, but also the uncertainty associated with the spherically mounted retroreflector (SMR) target and magnetic nests. These variations are implicit within the network adjustment and subsequent MCS-based uncertainty evaluation. However, the number of measurement samples is limited, and therefore cannot be thought of as a robust characterisation of these components of uncertainty. As a consequence, the SMR and magnetic nests have been explicitly included within the uncertainty budget (Table I).

Repeatable magnetic target nests are used to hold 1.5\( ^{\prime} \) (38.1 mm) diameter spherical targets such as SMRs, tooling balls or split bearings; this allows the same point in space to be measured by each instrument. The repeatability of these magnetic target-holding nests was experimentally evaluated by placing a tooling ball in the nest and measuring the runout (observed deviation about a central axis) in each of the three axes with a digital dial indicator 10 times for five different nests, thus totalling 150 runout measurements. The combined standard uncertainty for the magnetic nest, \( u(n_m) \), was determined as 1.48 \( \mu m \).

The SMR uncertainty, \( u(n_t) \), can be attributed to a mechanical centring tolerance of 6 \( \mu m \), with an equal probability applied to the tolerance band. Hence, a rectangular distribution can be assumed, and the standard deviation can be obtained as:

![Fig. 1. Reference measurement analysis for the uncertainty evaluation (with point uncertainty fields and coordinate system). The Y axis is parallel to the greatest length of the reference network; the Z axis is vertical.](image-url)
The coordinate definition ($n$) of the points in the reference network can be expressed as

$$n = n_{\text{m}} + n_{\text{t}} + n_{\text{n}}.$$  

An uncertainty estimate can subsequently be determined (Table I) as

$$u_c^2(n) = u^2(n_{\text{m}}) + u^2(n_{\text{t}}) + u^2(n_{\text{n}}).$$

**Analysis**

**V-STARS INCA3 Photogrammetric System**

V-STARS INCA3 is a purpose-built metric camera with an 8 Mpixel CCD sensor. It has a 21 mm focal-length lens and a $77^\circ \times 56^\circ$ field of view (Geodetic Systems Inc., 2005).

In addition to the Leica AT401 laser tracker measurements, the reference network was remeasured using the V-STARS INCA3 camera (Fig. 2), using additional scale bars for the bundle adjustment to determine scale but without any further knowledge of the reference network measurement.

![Fig. 2. Reference measurement with the V-STARS INCA3 system. The V-STARS photogrammetric network comprised 359 images and 853 object points, including the 11 reference points.](image-url)
network’s coordinate definition. The uncertainty evaluation is therefore based on six degrees of freedom (DoF) using an unweighted least squares adjustment, using the network of points from the laser tracker network as a reference and “best-fitting” the constellation of points measured using the INCA3. Table II summarises the best-fit result. Fig. 3(a) shows the individual coordinate discrepancies in each axis, for each reference point. Fig. 3(b) shows the magnitudes of the coordinate discrepancies and an indication of the levels of the overall 3D measurement uncertainty present. The standard deviation from the least squares fit residuals is 43\(\mu\)m; the standard deviation is similar in each of the three axes and shows a good 3D agreement.

Comparing the inter-point distances of the two datasets also compares the shapes of the two datasets. Here the standard deviation is 40.6 \(\mu\)m, with a maximum deviation of 101 \(\mu\)m; this is close to the standard deviation of the least squares fit, and is therefore consistent. The standard deviation of the coordinate transformation residuals is the main component of uncertainty included in the uncertainty estimate for the network measurement (Table III). The INCA3’s instrument specification (Geodetic Systems Inc., 2005) is 5 \(\mu\)m + 5 \(\mu\)m/m (at \(k = 1\)). The reference network spanned approximately 145 m; at this distance the system’s specified uncertainty is 77.5 \(\mu\)m (at \(k = 1\)); the authors’ uncertainty estimate shows that the system performed well within its specification with an uncertainty of 43.1 \(\mu\)m (at \(k = 1\)).

The coordinate definition of the photogrammetric measurement \((p)\) can be expressed as a function of the reference network \((n)\) and the best-fit residuals \((p_f)\) such that:

\[
p = p_f + n.
\]

This means that (Table III):

\[
u_c^2(p) = u_c^2(p_f) + u_c^2(n).
\]

Off-the-shelf Photogrammetric System

The off-the-shelf photogrammetric system comprised of a Nikon D700 DSLR fitted with a 28 mm Nikkor lens and VMS. The measurement was processed using a self-calibrating photogrammetric adjustment. Following the same processing chain, the standard deviations of the 6 DoF least squares fit residuals to the reference network coordinates (Fig. 4) gives a standard deviation of 186 \(\mu\)m (Table IV) and the inter-point distances give a standard deviation and maximum deviation of 155 and 364 \(\mu\)m, respectively. From Table IV the \(Y\) axis (Fig. 1) exhibits a larger degree of variation than the \(X\) and \(Z\) axes, which agreed with one another. The \(Y\) axis is aligned to the length of the reference network; this longer distance could be more sensitive to scaling errors which manifest themselves as \(Y\) axis errors. More generally, the high best-fit residuals dominate the uncertainty estimate (Table

<table>
<thead>
<tr>
<th>Results</th>
<th>Best-fit (6 degrees of freedom) transformation residuals (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(X)</td>
</tr>
<tr>
<td>Maximum error</td>
<td>0.042</td>
</tr>
<tr>
<td>Standard deviation of errors</td>
<td>0.025</td>
</tr>
</tbody>
</table>
V) and the total measurement uncertainty for the off-the-shelf camera is 186.6 μm (at \( k = 1 \)). This is likely to be a consequence of several limitations in comparison to the commercial system, the combination of which will increase the uncertainty of the target coordination within the self-calibrating bundle adjustment process. There are three contributing factors:

![Fig. 3. Comparison of V-STARS INCA3 coordinates after an unweighted least squares adjustment with reference coordinates at the 11 comparison points. (a) Target coordinate discrepancies from the reference network in each coordinate axis. (b) Magnitude of target coordinate discrepancies from the reference network.](image)
The camera had an unstable interior orientation. The focus of the Nikkor lens was fixed during image capture. However, instabilities in the physical fixture of the lens to the camera body and of the complementary metal oxide semiconductor (CMOS) imaging sensor to the camera body will contribute to small image-to-image geometry variations.

Fig. 4. Comparison of the DSLR and VMS bundle adjustment coordinates after an unweighted least squares adjustment with reference network coordinates. (a) Target coordinate discrepancies from the reference network in each coordinate axis. (b) Magnitude of target coordinate discrepancies from the reference network.
Fundamental to a high-quality result is the geometry of the imaging network with multiple convergent lines of sight to each target. Unlike the V-STARS state-of-the-art commercial photogrammetric system, the low-cost system does not have provision to connect to a host computer and carry out an online bundle adjustment as the images are captured. This limitation means that the operator does not receive any guidance as to where the photogrammetric imaging geometry should be improved during the capture process.

Retrotarget image quality is critical for a high-quality result. Whilst images were captured using retroreflective targets and an electronic flash with the low-cost system, there were no optimisations (such as multiple exposures and changes in exposure) to ensure optimal target image quality. This limitation is compounded by a reduction in retrotarget image quality following the camera’s Beyer colour correction that is integral to the design of the DSLR sensor (Luhmann, 2010).

Table III. Uncertainty estimate for V-STARS INCA3 measurement.

| Standard uncertainty component $u(x_i)$ | Source $(X_i)$ | Value of standard uncertainty $u(x_i)$ ($\mu$m) | Sensitivity coefficient $c_i = \frac{\partial f}{\partial x_i}$ | $u_i(n) = |c_i|u(x_i)$ ($\mu$m) |
|----------------------------------------|---------------|---------------------------------|-----------------|-----------------|
| $u(p)$                                 | Fit residuals with 6 degrees of freedom | 41.23              | 1               | 41.23           |
| $u(n)$                                 | Reference standard network uncertainty | 12.39          | 1               | 12.39           |

$u_i^2(p) = \sum u_i^2(p) = 1853.43 \mu m^2$

$u_i(p) = 43.05 \mu m$

Table IV. Summary of the DSLR/VMS best-fit results with the reference network points.

<table>
<thead>
<tr>
<th>Results</th>
<th>Best-fit transformation residuals (6 DoF) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>$Y$</td>
</tr>
<tr>
<td>Estimated uncertainty – mean (worst case)</td>
<td>0.085</td>
</tr>
<tr>
<td>Maximum error</td>
<td>0.151</td>
</tr>
<tr>
<td>Standard deviation of errors</td>
<td>0.086</td>
</tr>
</tbody>
</table>

Table V. Uncertainty contributions for the DSLR measurements.

| Standard uncertainty component $u(x_i)$ | Source $(X_i)$ | Value of standard uncertainty $u(x_i)$ ($\mu$m) | Sensitivity coefficient $c_i = \frac{\partial f}{\partial x_i}$ | $u_i(n) = |c_i|u(x_i)$ ($\mu$m) |
|----------------------------------------|---------------|---------------------------------|-----------------|-----------------|
| $u(p)$                                 | 6 DoF fit residuals | 186.16                    | 1               | 186.16           |
| $u(n)$                                 | Reference standard network uncertainty | 12.39              | 1               | 12.39           |

$u_i^2(p) = \sum u_i^2(p) = 34809.06 \mu m^2$

$u_i(p) = 186.57 \mu m$

(2) Fundamental to a high-quality result is the geometry of the imaging network with multiple convergent lines of sight to each target. Unlike the V-STARS state-of-the-art commercial photogrammetric system, the low-cost system does not have provision to connect to a host computer and carry out an online bundle adjustment as the images are captured. This limitation means that the operator does not receive any guidance as to where the photogrammetric imaging geometry should be improved during the capture process.

(3) Retrotarget image quality is critical for a high-quality result. Whilst images were captured using retroreflective targets and an electronic flash with the low-cost system, there were no optimisations (such as multiple exposures and changes in exposure) to ensure optimal target image quality. This limitation is compounded by a reduction in retrotarget image quality following the camera’s Beyer colour correction that is integral to the design of the DSLR sensor (Luhmann, 2010).
Comparison with Laser Tracker

In order to assess the photogrammetric systems’ suitability for large-volume measurement, current industrial practice must be taken into consideration in order to make meaningful comparisons. At present a laser tracker can be used either in a single-station configuration or networked together to minimise point uncertainty; however, the former is more common. A single-station laser tracker’s uncertainty was calculated using the reference network points; Table VI shows a summary. This summary is the result of 10 datasets from individual tracker stations: as some tracker positions are better placed than others, this should provide a balanced residual result. To ensure the experimental results are not unreasonable, Table VII has been constructed to compare the experimental results with those of the manufacturers’ specifications. The laser tracker shows consistent agreement with the manufacturer’s expectation, whereas V-STARS INCA3 performed significantly better than the manufacturer’s specification. However, the laser tracker network (as opposed to the single-station results) has a much lower measurement uncertainty than that of the other systems.

Conclusions

This paper highlights the capabilities of three optical metrology systems suited to large-volume industrial measurement. A laser tracker, a state-of-the-art commercial photogrammetric system (V-STARS INCA3) and a photogrammetric system based on an off-the-shelf camera of considerably lower cost (Nikon and VMS). The results have been characterised within the context of measurement uncertainty since this is a key factor in relation to meeting and verifying tolerances for critical measurements. Typically, at least a 95-45% (k = 2) measurement confidence is required for large-scale manufacturing measurements.

The impact of measurement confidence with reference to a design tolerance of ±250 μm for the measurement task undertaken for this analysis is summarised in Fig. 5. This data

<table>
<thead>
<tr>
<th>Results</th>
<th>Best-fit transformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Maximum error</td>
<td>−0.1148</td>
</tr>
<tr>
<td>Standard deviation of errors</td>
<td>0.0339</td>
</tr>
</tbody>
</table>

Table VII. Manufacturers’ specifications compared to experimentally derived standard measurement uncertainty.

<table>
<thead>
<tr>
<th>Laser tracker</th>
<th>Single station</th>
<th>Network</th>
<th>V-STARS INCA3</th>
<th>Nikon and VMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturers’ specifications</td>
<td>7.5 μm + 3 μm/m</td>
<td>n/a</td>
<td>5 μm + 5 μm/m</td>
<td>n/a</td>
</tr>
</tbody>
</table>
| System expectation at a maximum dimension of 14.5 m | 51.0 μm | n/a | 77.5 μm | 184.5 μm*
| Experimentally determined specification at 14.5 m | 51.8 μm | 12.4 μm | 43.1 μm | 186.6 μm |

*Figure based on the network adjustment error propagation for the worst-case target in the network.

© 2016 The Authors

The Photogrammetric Record © 2016 The Remote Sensing and Photogrammetry Society and John Wiley & Sons Ltd
demonstrates the impact of using a laser tracker in isolation when compared to a networked arrangement, although it should be noted that an industrial tracker network is unlikely to be quite as strong, as not all stations have a line of sight to all targets. Nevertheless, networking of instruments still yields significant improvements with respect to the associated uncertainty.

Fig. 5 also contextualises the INCA3’s performance and its suitability for these measurement tasks. The V-STARS INCA3’s results are comparable to (and indeed less than)
the laser tracker’s uncertainty as a single-station measurement instrument. Thus, for this application V-STARS INCA3 meets the uncertainty requirement and is a suitable substitute for the single-station laser tracker measurements. It should also be noted that the V-STARS system could be discounted as an instrument using the manufacturer’s specification alone. Further improvements could be made to the performance of the photogrammetric system if a global scale was accessible. This global scale could be generated via laser tracker network measurements.

The non-commercial photogrammetric system is working within its expected uncertainty estimation from the bundle adjustment, but this far exceeds the desired uncertainty level, and the tolerance band for this application (±250 μm) makes confidence in achieving the tolerance impossible. In its current configuration, the system could provide low-cost measurement for less critical tolerances, for example, ±1 mm across the 13.5 m × 8 m × 3 m volume used for this series of experiments.

ACKNOWLEDGEMENTS

This work has been carried out through a PhD sponsored by Airbus UK and the EPSRC Innovative Manufacturing Research Centre at the University of Bath (grant reference GR/R67507/0). Additionally, thanks to Jon Kimber (Hexagon Metrology), Nicolas Tanala (Solve Metrology/NTI/NRK), Craig Green (Solve Metrology/Horst Witte) and Airbus Broughton Tooling & Metrology for ongoing support with projects.

REFERENCES


Martin et al. Comparison between two photogrammetric systems and a reference laser tracker network

Résumé

Cet article détermine les performances de deux systèmes photogrammétriques en termes d’incertitude de mesure dans un contexte industriel. Le premier système – le V-STARS inca3 de Geodetic Systems Inc. – est une solution de mesure disponible dans le commerce. Le second système est constitué d’une caméra numérique Nikon D700 disponible sur étagère équipée d’un objectif 28 mm Nikkor et du logiciel de recherche VMS (Vision Measurement Software). Les incertitudes de ces deux systèmes sont estimées par comparaison avec un réseau de points étalonnés au moyen d’un laser tracker Leica AT401. Ces points ont une incertitude moyenne de 12,5 μm et s’étendent sur une distance maximale d’environ 14,5 m. Les incertitudes des deux systèmes sont alors déterminées. Le V-STARS inca3 a une incertitude de 43,1 μm, meilleure que les spécifications du constructeur, tandis que la combinaison D700/VMS a une incertitude de 187 μm.

Zusammenfassung


Resumen

En este trabajo se determina la capacidad de dos sistemas fotogramétricos en términos de su incertidumbre en la medición en un contexto industrial. El primer sistema – V-STARS INCA3 de Geodetic Systems Inc. – es una solución disponible en el mercado. El segundo sistema comprende una cámara digital Nikon D700 equipada con un objetivo Nikkor de 28 mm y el software de desarrollo Vision Measurement Software (VMS). La estimación de la incertidumbre de estos dos sistemas se determina con referencia a una constelación de puntos calibrada que ya ha sido determinada por un sistema de seguimiento láser Leica AT401. Los puntos calibrados tienen un promedio de incertidumbre estándar de 12,5 μm, que se extiende una distancia máxima de aproximadamente 14,5 m. Posteriormente, se determinó la incertidumbre de los dos sistemas. V-STARS INCA3 tenía una incertidumbre estándar estimada de 43,1 μm, mejorando de este modo las especificaciones del fabricante; la combinación D700/VMS conseguía una incertidumbre estándar de 187 μm.

摘要

本文之目的在于以量测不确定性，确认两套摄影测量系统，应用于工业量测时的能力。第一个系统是Geodetic Systems公司之V-STARS INCA3，为商业化之市售量测解决方案。第二个系统则由消费者型尼康D700数码相机，配备28mm尼克尔镜头，和研究型的视觉测量软件(VMS)，这系统之量测不确定性，以使用徕卡AT401激光追踪器量测所得一组校正点为参考标准，校正点之平均标准不确定性为12.5微米。最大跨距约14.5米。两个系统的不确定性经以上比对，V-STARS INCA3之不确定度为43.1微米，优于其制造商的规格：D700/ VMS系统之标准不确定度为187微米。
学霸图书馆
www.xuebalib.com

本文献由“学霸图书馆-文献云下载”收集自网络，仅供学习交流使用。

学霸图书馆（www.xuebalib.com）是一个“整合众多图书馆数据库资源，提供一站式文献检索和下载服务”的24小时在线不限IP图书馆。

图书馆致力于便利、促进学习与科研，提供最强文献下载服务。

图书馆导航：
图书馆首页 文献云下载 图书馆入口 外文数据库大全 疑难文献辅助工具