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Resection methodology for PSP data processing: Recent experiences in NAL

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Abstract. PSP data processing, which primarily involves image alignment and image analysis, is a crucial element in obtaining accurate PSP results. There are two broad approaches to image alignment: the algebraic transformation technique, often called image-warping technique, and resection methodology, which uses principles of optical photogrammetry. Resection is found to have higher resolution, especially when large gradients in pressure or significantly three-dimensional regions have to be resolved, and even with flat models when the camera angles are large. A processing software based on these methodologies has been successfully developed and validated and is currently in use at the Experimental Aerodynamics Division of the National Aerospace laboratories, Bangalore.

In this paper, we show the merits of resection methodology through two examples: (a) a wing-body model in transonic flow ($M = 0{\cdot}8$) and (b) a simple delta wing in low supersonic flow ($M = 1{\cdot}8$). The PSP system utilized for both the cases involve Optrod-B1 paint, a specially designed UV lamp for excitation and two scientific grade CCD cameras for imaging. Typical results are shown using both the algebraic transformation approach and resection methodology.

Keywords. Pressure-sensitive paint; resection; delta-wing.

1. Introduction

The technique of pressure-sensitive paint (PSP) for measuring surface pressure fields on wind tunnel models is well known. The method, as described elsewhere (Venkatakrishnan 2004; Channa Raju & Viswanath 2005; Channa Raju *et al* 2005), involves coating the model with a compound of fluorescent material, which is then illuminated with light of appropriate wavelength to excite the coating material. The pressure-sensitive emission intensity distribution is imaged with a scientific grade CCD camera during wind tunnel tests. It is common practice to use a two-component paint, a pressure-dependent component (blue) and a reference component (red), which is sensitive only to excitation intensity and not to pressure, so as to account for non-uniform intensity of illumination on the model surface. PSP data processing is a multi-step process that includes (a) calibration of the paint and converting image intensities to pressure, (b) application of corrections for non-ideal, real-world effects of optical distortions during imaging, and (c) determining and applying a transformation from image to model coordinates.

Most PSP methods using binary paint perform a “ratio-of-ratios” between a reference (wind-off) image and a pressure (wind-on) image, each of which are normalized by the illumination to compensate for spatial and temporal variation in light intensity. The images have to be aligned with each other prior to normalization and ratioing. The process of alignment is termed “registration”. This procedure is carried out using one image (usually the wind-off illumination-sensitive image) as a “base image” and warping the other images on to this image. This step is usually followed by mapping of the image co-ordinates on the three-dimensional model in a method called *resection*. It has long been recognised that the accuracy of a pressure-sensitive paint system depends on many parameters among which image registration is the most important. There are two approaches to obtaining the ratio-of-ratios. The first, more commonly used, is to use some form of image transformation method to warp all the images on to a base image, which is chosen from among the four images. After completion of the ratioing, map it on to the surface grid of the model using resection. The alternative is to form the ratios in model rather than image coordinates by first individually resecting all images on to the model grid using photogrammetric techniques. The first approach, more commonly used in PSP work, seems suitable and adequate when the model surface is largely flat (with minimum transverse curvature) and model deflections and deformations are small between wind-off and wind-on images. However, more accurate results can be obtained by resection prior to ratioing, particularly for three-dimensional models in general and with model deflections between wind-off and wind-on; simple image warping techniques are not sufficient and the error is shown to be significant (Venkatakrishnan 2004). Recently, a data processing methodology and software, based on the resection approach which uses principles of optical photogrammetry was developed at NAL and demonstrated to show improved results in such cases (Venkatakrishnan 2004).

However, even when the model is flat and has no curvature, large camera angles may necessitate the use of the resection approach for better results, as is brought out in results presented here. In this paper, we use two examples from our PSP experiments to illustrate the merits of resection-based approach. In the first application, we show the effectiveness of the resection method in capturing large pressure gradients on a body with significant curvature and in the second, we show how large camera angles can lead to a skewed ratioed image even on a flat delta-wing model with the transformation approach and its improvement with the resection approach.

1.1 *Image processing methodology*

In the following sections, the two approaches to PSP data processing are described. First, the algebraic transformation chosen for this exercise which is a third-order polynomial method is described, following which the photogrammetry-based resection approach is outlined.

1.1a *Algebraic transformation approach:* These methods are suited mainly for rigid body motion of two-dimensional objects with small deformations, while being reasonably good approximations for small motions of three-dimensional objects. The geometry of the model, amount of deformation, number of markers, accuracy required and computational resources determine the method chosen.

Polynomial transformations can usually account for any combination of model movement and deformation as long as the series is carried out to sufficiently high order. A first-order transformation requires only three targets, but second- and third-order polynomial transforms need a minimum of 6 and 10 targets respectively. This takes the form of a polynomial series expansion:

$$
\begin{aligned}
x &= a_{00} + a_{10}x' + a_{11}y' + a_{20}x'^2 + a_{21}y'^2 + a_{23}x'y' + \dots, \\
y &= b_{00} + b_{10}x' + b_{11}y' + b_{20}x'^2 + b_{21}y'^2 + b_{23}x'y' + \dots.
\end{aligned}
\tag{1}
$$

1.1b *Resection on to surface grid:* Transformation from image-plane coordinates (x, y) to model space coordinates (X, Y, Z) is required in order to be able to determine the surface pressure at a physical point of interest in the model. This is termed *resection of an image onto the model surface grid*. A camera model, based on perspective projection, was augmented with a lens distortion model for this approach. The lens of the camera is modelled by a single point called perspective centre, which is also the origin of the image coordinate system in model coordinate space. A three-step approach is used here. The first step involves an initial guess for the camera exterior parameters (camera location and orientation) that are obtained either by the direct linear transform method or by using the nominal values of the focal length and image plane (CCD) size. The second step estimates the parameters of the forward camera model (which are intrinsic to the camera) by minimizing the weighted sum of squared differences between the observations and the model. The Levenberg–Marquardt method is then used for the optimization problem. Further details of this method can be obtained in Venkatakrishnan (2004).

2. Experimental details

2.1 *PSP instrumentation and arrangement*

The PSP system at NAL consists of an UV-flash lamp, two scientific grade CCD cameras, the calibration equipment and an image processing software package from OMT GmbH, Germany. Excitation of the PSP on the model was provided by a xenon flash lamp emitting UV light in the range of about 350 nm wavelength. Optimum distribution of illumination on the entire model surface was obtained by using four illuminator heads connected to the lamp system by four 15 m long optical fibre cables. The paint emission data were acquired by two air-cooled scientific grade 12-bit CCD slow-scan cameras with resolutions of 1280×1024 pixels. The image acquisition was made by a PC-based data acquisition system based on two separate PCI-cards. The camera and illumination were triggered and controlled by LabVIEW-based software. The image integration time was about nine seconds for the first application and six seconds for the second, so as to have a large pixel fill ratio in the CCD array (to have large signal to noise ratio). The sequence of measurement involved acquisition of images from the two cameras (the pressure-sensitive and the intensity-sensitive): (a) ambient pressure and temperature, (b) dark images (c) pre-run wind-off images, (d) wind-on images, and (e) post-run wind-off images. The temperature data in the settling chamber and on the model surface and lee-surface pressures were also acquired simultaneously during the run. An objective of 12 mm focal length was utilised in each of the cameras in order to provide maximum spatial resolution of PSP images. As a result, a small area of wing-tip (on one of the wings of the wing-body model) could not be imaged. The models were coated with the well-known Optrod-B1, a pyrene-based binary pressure-sensitive paint supplied by M/s Optishe Messtechnik GmbH, Germany.

Static pressure measurements on the model were made using a 16-port, 10-psia ESP scanner. The uncertainty estimated was in the range of $\Delta C_p < \pm 0{\cdot}02 C_p$.

The temperature drop experienced in a blowdown tunnel such as that used in the present study, has some effect on the results due to the slight (∼ 0·35%) temperature sensitivity of the PSP. A temperature correction using the mean temperature hypothesis was developed and successfully applied by Channa Raju & Viswanath (2005) and has also been used here.

2.2 *Experiments on wing-body model*

The experiments were conducted in the NAL 1·2 m trisonic blowdown test facility with a square working test-section of 1·2 m × 1·2 m. The tunnel can provide Mach numbers ranging from 0·2 to 4·0 and a Reynolds number range of 8×10^6 to 60×10^6 per metre; typical blowdown duration is about 20 seconds. The PSP measurements were conducted in the solid wall test-section of the tunnel with optical access provided by the modified side wall-mounted Schlieren window Figure 1a). The model chosen was a wing-body model supported in the vertical plane using a beta sting of 10° to provide model incidence. The geometric detail of the aircraft model which was made of high strength steel is shown in figure 1b. The model had a

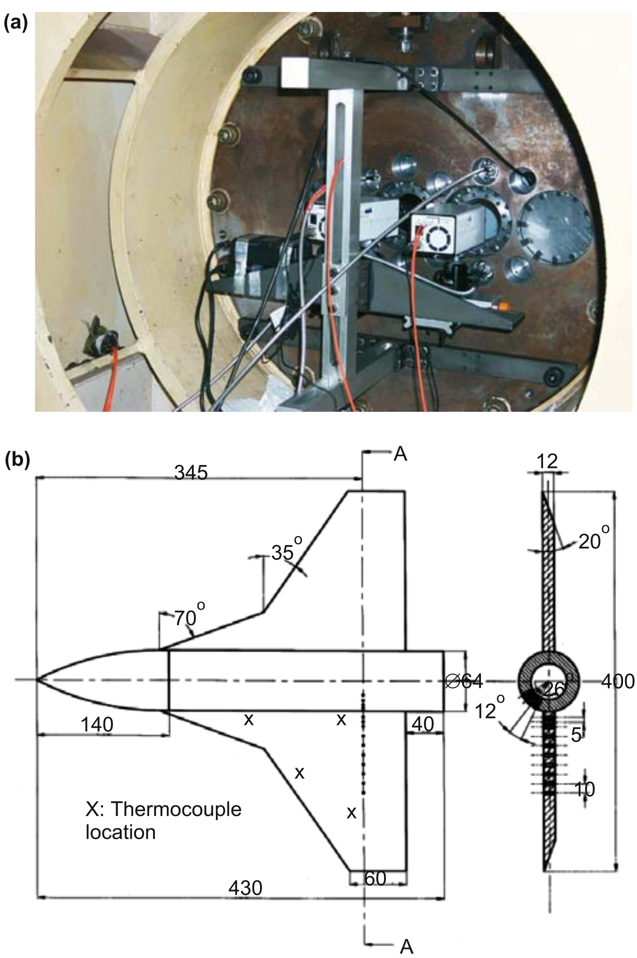

Figure 1. PSP arrangement and model details (1·2 m trisonic tunnel). **(a)** PSP system installed on the test section of 1·2 m trisonic wind tunnel. **(b)** Details of the aircraft wing–body model.

planform typical of combat aircraft with wings of constant thickness and beveled leading and trailing edges, for simplicity in fabrication. The model with an overall length of 430 mm and a full span of 400 mm was instrumented with four thermocouples and a series of 14 spanwise static pressure ports (ID 0·8 mm) on the lee-side of one of the wings, as shown in figure 2. Three static pressure ports on the wing closer to the wing/fuselage junction were 5 mm apart and the rest were 10 mm apart. Four static pressure ports on the fuselage were located at ϕ values of 28°, 40°, 52° and 64° (12° apart, measured from the symmetry plane on the top surface) as shown in figure 1b.

The PSP measurements were made at two Mach numbers of 0·6 and 0·8 and angles of attack of 6° and 10°, using two beta stings. Further details can be found in Channa Raju & Viswanath (2005).

2.3 *Experiments on the delta-wing model*

The experiments were conducted in the NAL 0·3 m trisonic blowdown test facility with a square working test-section of 0·3 m × 0·3 m. The tunnel can provide Mach numbers ranging from 0·2 to 4·0 and a Reynolds number range of 3×10^6 to 40×10^6 per metre. Supersonic Mach numbers are generated using fixed nozzle block liners. All tests were carried out with the

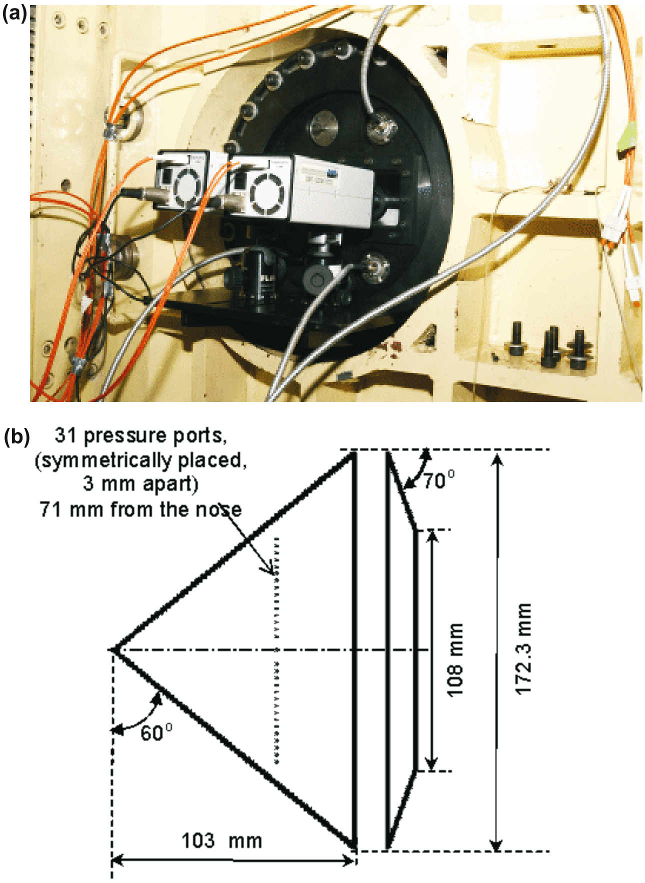

Figure 2. PSP arrangement and model details (0·3 trisonic tunnel). **(a)** PSP system installed on the test-section of 0·3 m trisonic tunnel. **(b)** Details of the delta-wing model.

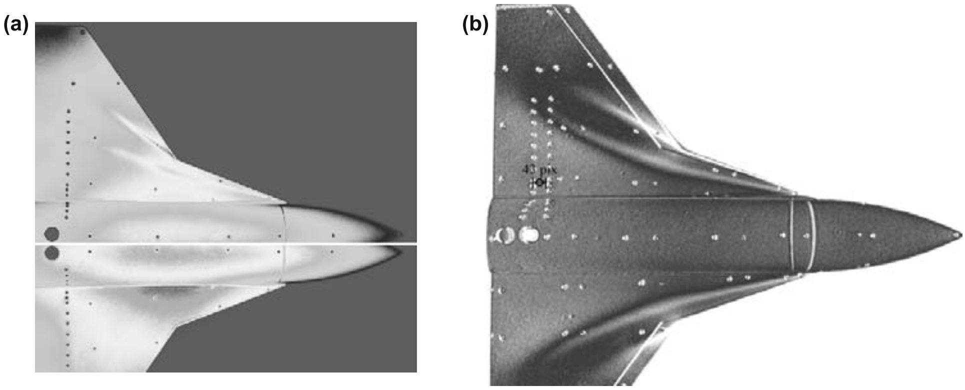

Figure 3. Image registration. **(a)** Image of top-half of the model compared between wind-off and wind-on conditions. **(b)** Marker misalignment due to camera perspectives.

tunnel total temperature at 303°K. The PSP measurements were conducted in the supersonic test section and schlieren window locations were utilized for optical access. The model was supported in the vertical plane using a beta sting of 10°.

Figure 2a shows geometric details of the 60° sweep delta-wing model which was made of high strength steel. The model had a simple, single delta-planform with beveled leading edges. It possessed an overall length of 103 mm and a full span of 172·3 mm, instrumented with 31 span-wise static pressure ports (i.d. 0·8 mm) on the lee-side of the wing, as shown in figure 2a. Details can be found in Channa Raju *et al* (2005).

The schlieren window arrangement was as outlined in the previous section, however, due to space constraints; there was a large angle between the two cameras. The effect of this is seen in the next section.

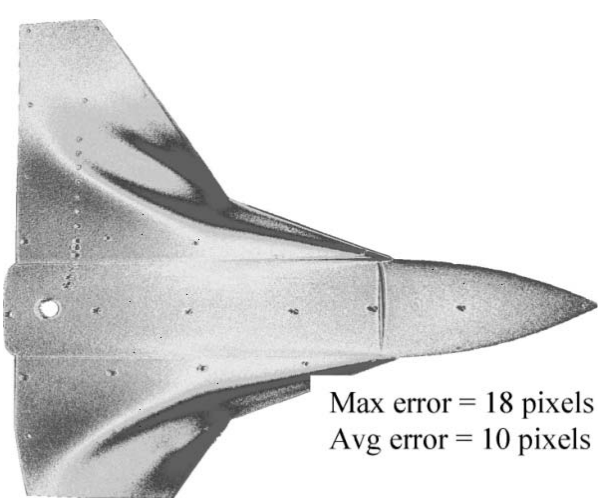

Figure 4. Field image using image-warping approach showing maximum and average errors in alignment.

3. Results and discussion

3.1 *Wing-body model*

A comparison of the misalignment in marker positions due to model displacement between wind-off and wind-on conditions and due to two different camera perspectives for the wing-body model is shown in figures 3a and b respectively. It may be noted that the effect of model displacement is very small (very few pixels) when compared to that of camera positions (approximately 43 pixels).

The field image showing maximum and average errors in image registration using the third-order polynomial approach is shown in figure 4; for the imaging conditions, the maximum

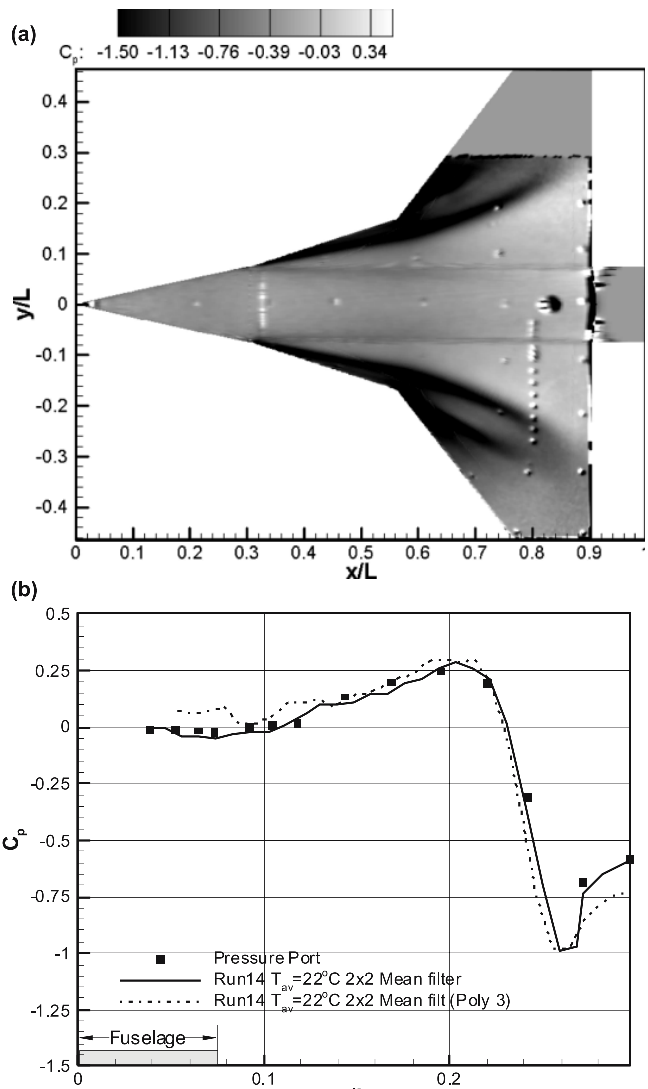

Figure 5. Results of the aircraft wing-body model. **(a)** C_p on surface grid using resection-before-ratio approach. **(b)** Comparison of mean pressure at a section from PSP methods and pressure ports.

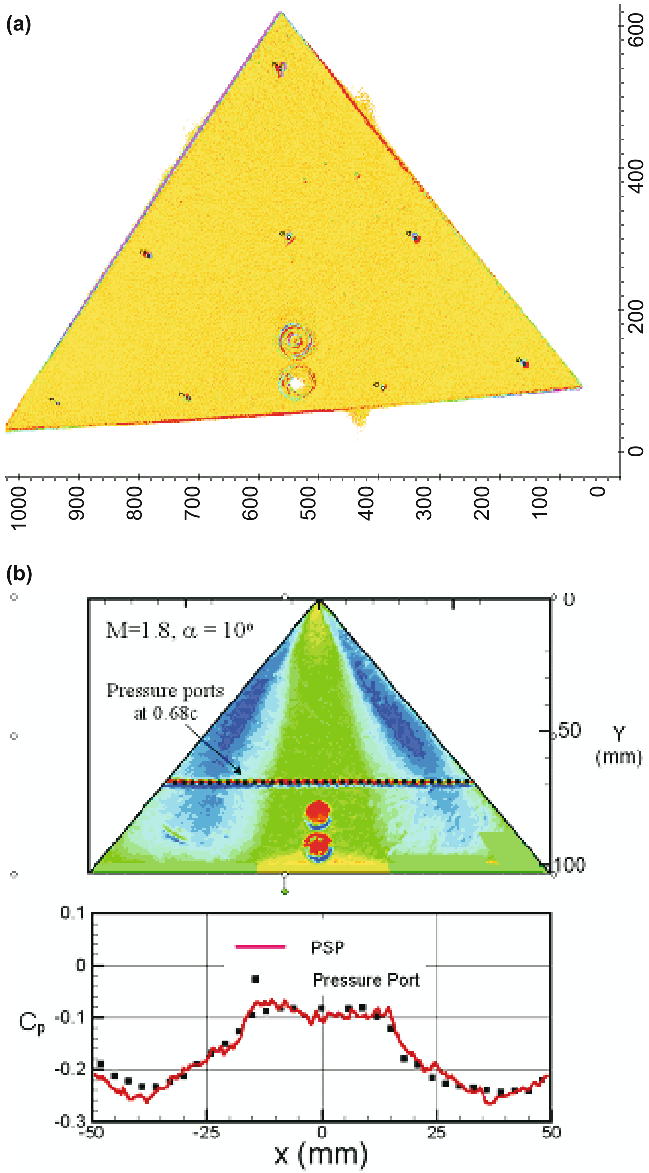

Figure 6. Results of the delta-wing model. **(a)** Skewed field image of the delta-wing model obtained using transformation approach. **(b)** Pressure map and comparison of PSP data with pressure port data.

error of 18 pixels corresponds to an error of about 7 mm in physical dimensions, which is not small.

In order to compare the two approaches, data were compared from both against conventional pressure port data. The resection-before-ratio approach is used to directly obtain C_p on the grid using the camera model outlined in Venkatakrishnan (2004). The maximum error in pixel location for each grid point was about 0·34 pixels (figure 5a). The image-warping approach uses the polynomial (order 3) transform, which is then ratioed in the normal way. The ratioed image is then resected onto the grid with the same 2×2 filter as for the direct resection approach. A comparison of C_p data from the two methods at the same axial station close to the leading edge of the wing ($x/L = 0{\cdot}35$) across the entire model (cutting both fuselage and wings) is shown in figure 5b. The differences in the resolution of the two methods can be clearly seen. The minimum C_p (vortex core) obtained for the direct resection case is lower than the polynomial case. This is caused by the smoothing effect of the image registration step using the polynomial approach. It is clear that the resection method is able to better pick up the regions of large pressure gradients, with greater accuracy.

3.2 *Delta-wing model*

While the resection-based approach is not in general needed for PSP models without significant curvature, it was necessitated here due to the unavoidable large viewing angle of one of the cameras. A field image obtained using polynomial transformation for the delta-wing model is shown in figure 6a. It may be seen that the large angle between the two cameras has resulted in a skewed field image. Furthermore, in spite of the model being flat, the errors in registration are considerably large (> 20 pixels), which can clearly seen from large displacements of marker points in the field image. The result of resection method is shown in figure 6b along with comparison of PSP with pressure port data. It may be seen that not only are the pressure gradients well-mapped, the comparison with pressure port data is also extremely good. This clearly shows that even for flat models when viewing angles are large, the resection method is able to provide pressure data to good accuracy.

4. Conclusions

The effectiveness of resection methodology over image processing in PSP data processing is examined using two applications. The resection is found to have higher resolution, especially when large gradients in pressure or significantly three-dimensional regions have to be resolved, and is to be preferred, despite slightly larger computing time. Additionally, it is seen that resection can yield improved results on even flat models without curvature when the camera angles are large. The successful application and favourable results from the resection approach promise improved applicability of PSP to complex configurations and accuracy comparable to conventional measurements.

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