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ABSTRACT

The National Physical Laboratory (NPL) and Loughborough University have investigated the use of a number of instruments for the characterisation of the external form and layer thickness of targets that will be used for inertial confinement fusion experiments, as part of the development of the European High Power laser Energy Research (HiPER) facility. The targets are nominally 1.8 mm outer diameter spherical transparent polymer shells with a wall thickness of approximately 50 µm. Some representative planar samples with varying wall thicknesses were also measured. NPL used a tactile micro-co-ordinate measuring machine to measure the average radius and form of the spherical targets. A scanning laser confocal microscope was used to take qualitative measurements of the target's inner and outer surfaces to investigate the damage caused by tactile probing. The targets and planar samples were also measured on a coherence scanning interferometer and an optical coherence tomography system at Loughborough University. The investigations indicate that the applied probing force associated with the tactile measurements resulted in damage to the samples. The results suggest that current optical technology is capable of producing qualitative images of the target form. Using optical modelling it is proposed that quantitative measurements of internal surfaces can be made from data collected from a modified coherence scanning interferometer.

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Approved on behalf of NPLML by Ian Severn, Head of Engineering Measurement Division

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1 HIPER TARGET VERIFICATION REQUIREMENT

HiPER is the High Power laser Energy Research facility based at the Central Laser Facility of the Rutherford Appleton Laboratory. HiPER is being designed to demonstrate the feasibility of laser driven fusion as a future energy source. The facility will also enable the investigation of the science of extreme conditions – accessing regimes which cannot be produced elsewhere on Earth (temperatures of hundreds of millions of degrees Celcius, billion atmosphere pressures, and very large electric and magnetic fields).

Specific targets are required to contain the fusion materials (dueterium or tritium) in the form of liquid, solid or foam. The targets are likely to be thin-walled spherical shells in glass or polymer and may have various mounting features. The key measurement requirements for the targets are:

- sphericity of the shell (manufacturers tolerance is 50 nm);
- thickness of fuel ice layer (nominally 200 µm);
- internal roughness of fuel ice layer (nominally 1 µm).

The nano-crystalinity of the fuel ice must also be measured, as well as the pore size and pore distribution of the foam seed layer.

2 PROPOSED MEASUREMENT SOLUTION

2.1 SUPPLIED SAMPLES

The Central Laser Facility, Rutherford Appleton Laboratory, supplied NPL and Loughborough University with paralene targets made to a similar standard as those that will be used in the proposed reactor. To measure polymer layer thickness, a representative flat sample was supplied for optical measurement at Loughborough University.

2.2 EQUIPMENT AVAILABLE FOR USE

NPL's Engineering Measurement Division maintains a range of dimensional metrology instruments to support both its core measurement and calibration services and its small-scale, freeform and large-scale metrology research. The following instruments were used to measure the fusion targets:

1) Zeiss F25 micro co-ordinate measuring machine (micro-CMM) - capable of making measurements of geometry to sub-micrometre accuracy (NPL),
2) laser scanning confocal microscope (LSCM) (NPL),
3) coherence scanning interferometer (CSI) (Loughborough University) and
4) optical coherence tomography instrument (OCT) (Loughborough University).

3 TACTILE MEASUREMENTS

3.1 TARGET MOUNTING

To carry out tactile measurements, the targets had to be mounted securely within the micro-CMM's measurement volume. This was achieved by mounting individual targets onto the tips of hypodermic needles using a suitable adhesive (cyanoacrylate).

The mounted targets were held in a vertical orientation in a small precision chuck on top of a rotation stage. The targets were mounted nominally in the centre of the micro-CMM's measurement volume. An image of a mounted target is shown in Figure 1.

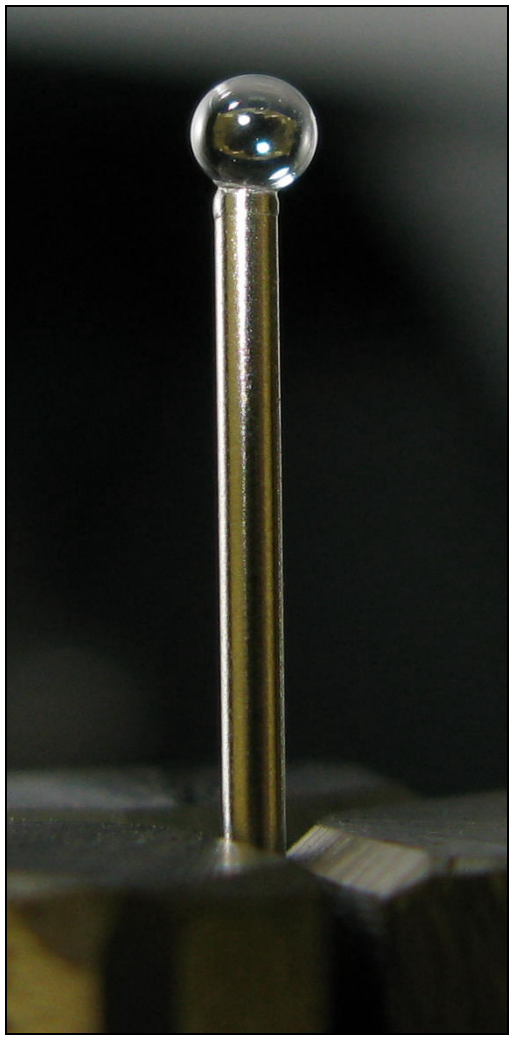

Figure 1 A mounted target

3.2 PROBING FORCE

One limitation in the measurement of the targets using tactile co-ordinate metrology is that the contact force from the stylus tip of the micro-CMM could damage the target. The probing force of the micro-CMM has been determined to be in the order of 15 mN on initial contact. After this initial contact force, the machine automatically reduces the contact force to 8 mN to record a measurement point.

Preliminary measurements taken with this contact force proved catastrophic, resulting in puncturing of the target at the pole. This puncturing is shown in Figure 2.

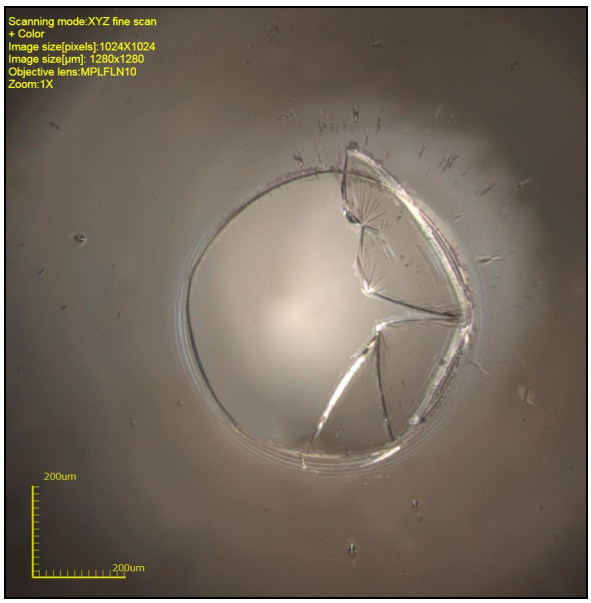

Figure 2 Resulting damage from repeated contact at 15 mN (picture obtained using the LSCM)

All subsequent measurements of the targets were taken at 20 % of the nominal machine probing force. This results in an estimated probing force of 3 mN on contact and 1.6 mN at measurement.

3.3 MEASUREMENT PROCEDURE

The targets were measured using a micro-CMM incorporating a 300 µm stylus tip. Two different probing strategies were used. The first strategy is similar to that advised in ISO 10360 series for probe acceptance tests using twenty-five point measurements evenly distributed over the upper hemisphere. However, to accurately determine the form of the HiPER targets, more measurement points are required. The second strategy consisted of an array of 395 points evenly distributed over the surface of the upper hemisphere of the HiPER target.

Two fitting methods were used:

1) The Gaussian least squares fitting method (LS), which fits a sphere through all the data points such that the sum of the squares of the residuals is minimised. This is an ideal fitting method for diameter and radius calculations
2) The minimum zone method (MZ), which defines two concentric spheres that just contain the profile. This is an ideal fitting method for form measurement.

3.4 MEASUREMENT RESULTS

The aim of this study was to take a set of quantitative measurements of diameter and form using a tactile micro-CMM. The results obtained from a tactile investigation of the targets are shown in Table 1 and Table 2.

Table 1 Quantitative diameter measurements of the targets using two measurement strategies (measured using the micro-CMM)

	Measurement 1 /mm	Measurement 2 /mm	Measurement 3 /mm	Mean /mm	σ /mm
25 points – LS Sphere Fit	1.834 8	1.834 8	1.834 8	1.834 8	0.000 04
395 points – LS Sphere Fit	1.835 0	1.835 0	1.834 9	1.835 0	0.000 05

Table 1 shows the six diameter measurements. The means from the two measurement strategies show a variation of 200 nm. This implies that there is very little advantage to taking 395 measured points over 25 measured points when determining diameter.

These results are shown graphically in Figure 3. It can be seen that there is no statistically significant trend in the measurement data.

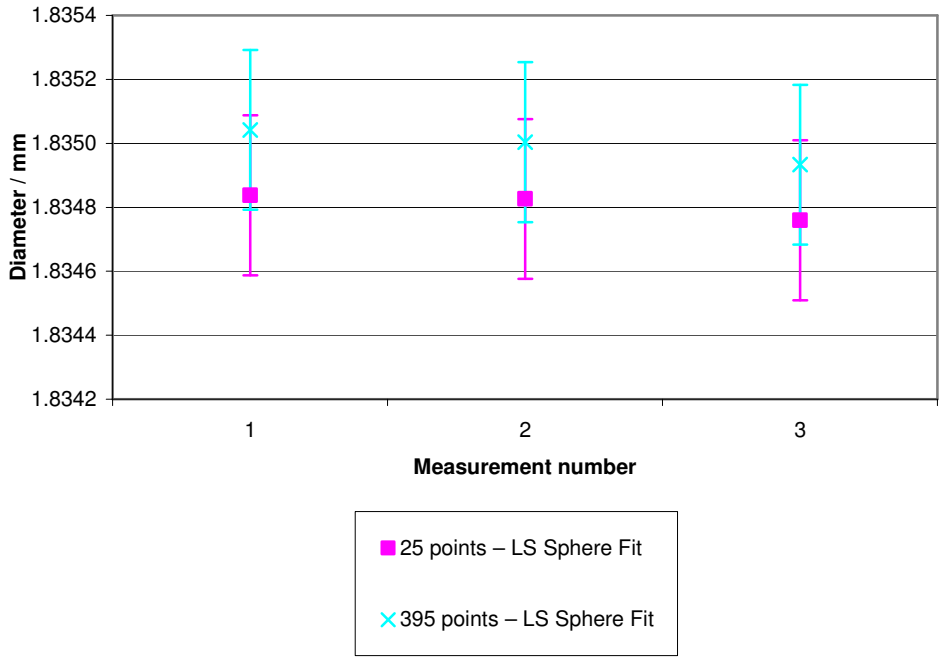

Figure 3 A graph showing the variation of diameter measurements over three measurements for two different measurement strategies (measured using the micro-CMM). The uncertainty bars represent the maximum permissible volumetric error of the micro-CMM (± 250 nm)

Table 2 Quantitative form measurements of the targets using two measurement strategies (measured using the micro-CMM)

	Measurement 1 /mm	Measurement 2 /mm	Measurement 3 /mm	Mean /mm	σ /mm
25 points – MZ Sphere Fit	0.001 4	0.001 5	0.000 9	0.001 3	0.000 27
395 points – MZ Sphere Fit	0.001 9	0.002 0	0.001 9	0.001 9	0.000 06

Table 2 shows the six form measurements. The means from the two measurement strategies show a variation of 600 nm. This implies that there is a difference between form determined by taking 395 measured points and 25 measured points. It is likely that the form calculated from the 395 measured data points is more accurate.

These results are shown graphically in Figure 4. It can be seen that there is no statistically significant trend in the measurement data.

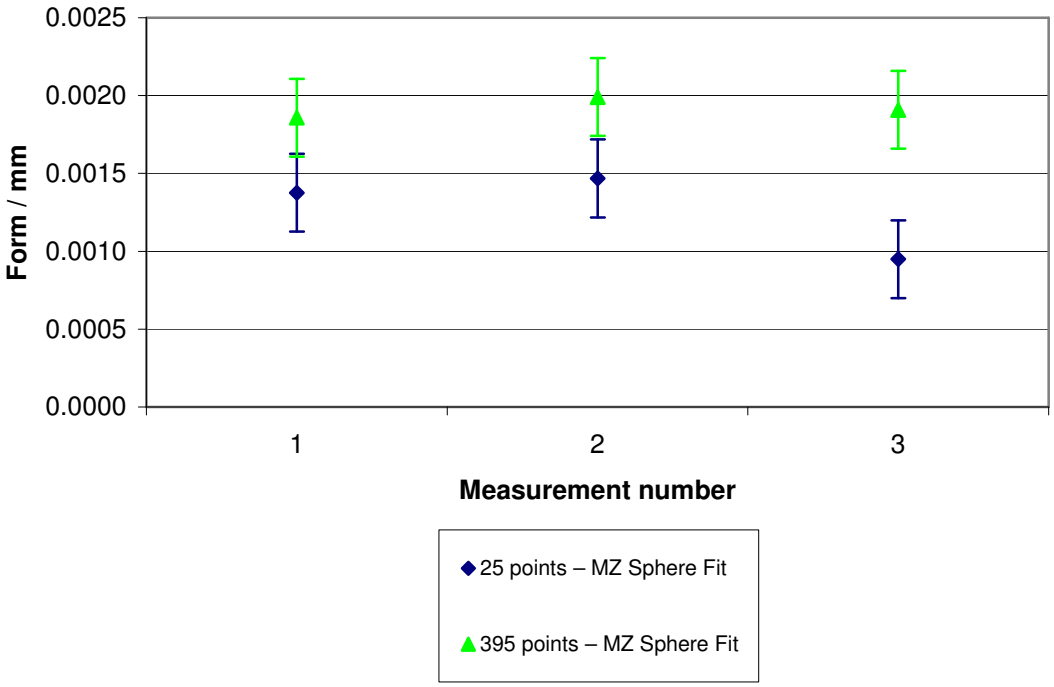

Figure 4 A graph showing the variation of form measurements over three measurements for two different measurement strategies (measured using the micro-CMM). The uncertainty bars represent the maximum permissible volumetric error of the micro-CMM (± 250 nm)

There are no noticeable trends in the diameter measurements of the target, however, due to the delicate nature of the target it is probable that the shell of the target is being damaged during tactile measurement.

The pole of a mounted target was investigated using the LSCM to qualitatively inspect the surface for damage or contamination. These images are shown in Figure 5.

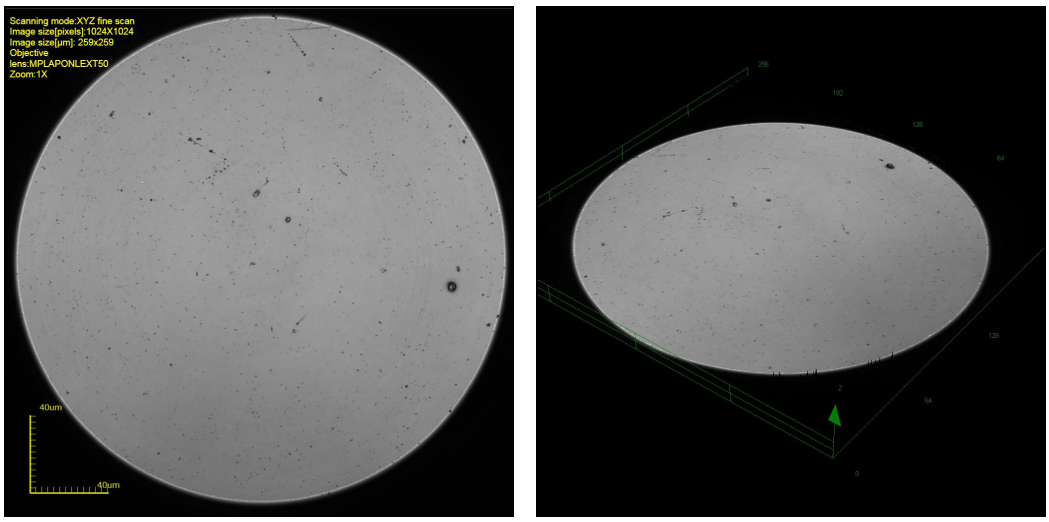

Figure 5 Qualitative surface measurements taken before micro-CMM measurement (images taken using the LSCM)

After measurements were taken on the micro-CMM, a further set of qualitative measurements was taken again to evaluate any damage. These images are shown in Figure 6.

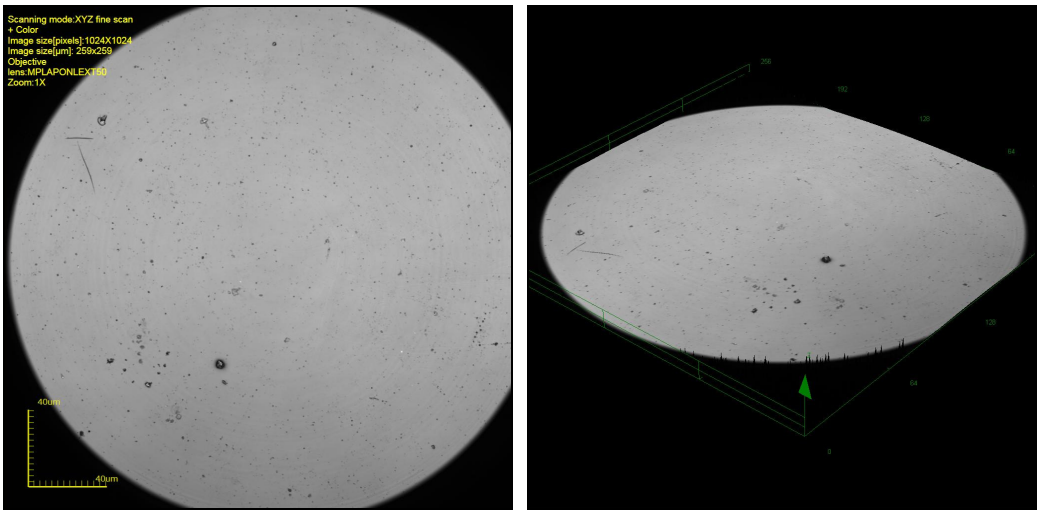

Figure 6 Qualitative surface measurements taken after micro-CMM measurement (images taken using the LSCM)

It can be seen that there is some contamination on the surface of the targets both before and after measurements were taken on the micro-CMM. The images taken after tactile micro-CMM probing do not reveal any significant damage sustained to the external surface of the target.

A set of images was also taken using the LSCM of the internal surface of the targets shell. The images are shown in Figure 7 and reveal significant internal damage to the target.

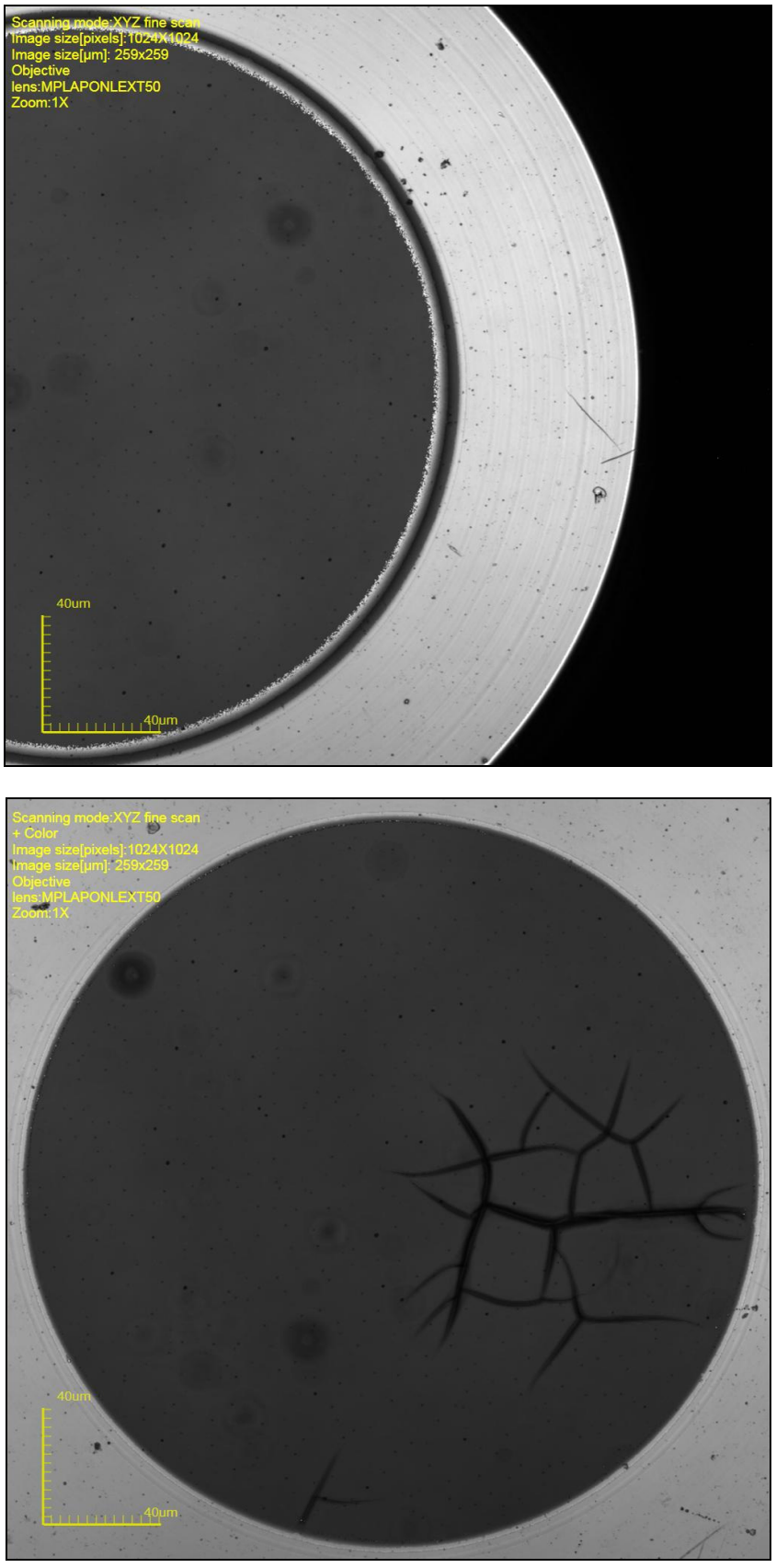

Figure 7 Qualitative measurements of the internal surface (the darker surface) taken before (top) and after (bottom) micro-CMM measurement (images taken using the LSCM)

3.5 CONCLUSIONS ON TACTILE MEASUREMENTS

It can be clearly seen from the LSCM images that extensive damage is being done to the targets during tactile probing, even with a contact force as small as 3 mN. No visible damage is being sustained on the outer layers, but internal damage is such that, if repeated measurements were taken, failure would occur (similar to that shown in Figure 2).

Should any metrology be performed on the targets in the future, it is the recommendation of NPL that non-tactile measurement must be used, or that tactile measurements must exert forces well below 3 mN.

4 OPTICAL MEASUREMENTS

4.1 CSI PERFORMANCE

Coherence scanning interferometry is an increasingly popular method used to measure surface profile. Essentially a CSI is a white-light interference microscope that scans the object through focus. The interference effect causes a burst modulation of the image intensity when the object passes through focus. From the phase and amplitude of the modulation the position of the surface can be found to interferometric (nanometre) precision.

The instrument used for measuring the fusion targets was a Zygo Newview 5000 CSI fitted with a 0.55NA objective (50×), which gives a lateral resolution of around 0.5 µm. The standard software supplied with the instrument (Metro Pro) was not suitable for the required analysis, so, instead, the raw interference data (interferograms) were taken from the instrument and processed in MATLAB®. The resulting, processed interferograms are presented in this document.

Sections through the raw interferograms corresponding to the 10 µm and 2 µm coatings of the representative polymer thickness samples are shown in Figure 8 and Figure 9. The strong signal return arises from the reflection at the polymer/air interface. Taking the refractive index of paralene as $n = 1.65$ we would expect approximately 6% reflection from this surface. The reflection from the polymer/glass interface is weaker. Taking the refractive index of glass to be $n = 1.5$ we would expect this reflection to be approximately 0.2% of the incident light intensity. For the case of the 10 µm step no interference signal can be seen. For the case of the 2 µm step there is a small modulation. This can be seen in Figure 10, which is a magnified region of Figure 9.

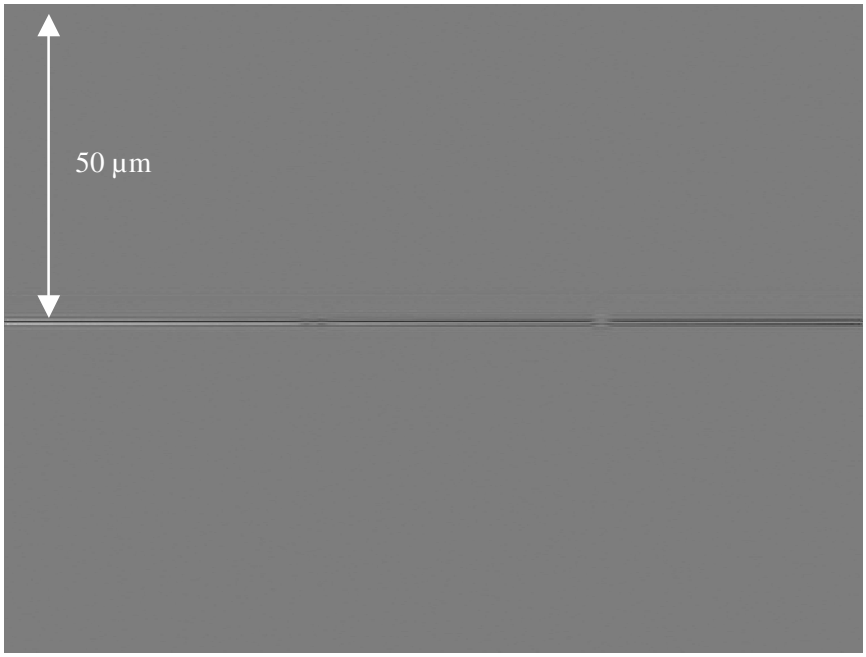

Figure 8 Raw interferogram section obtained on the 10 µm coating (measured using the CSI)

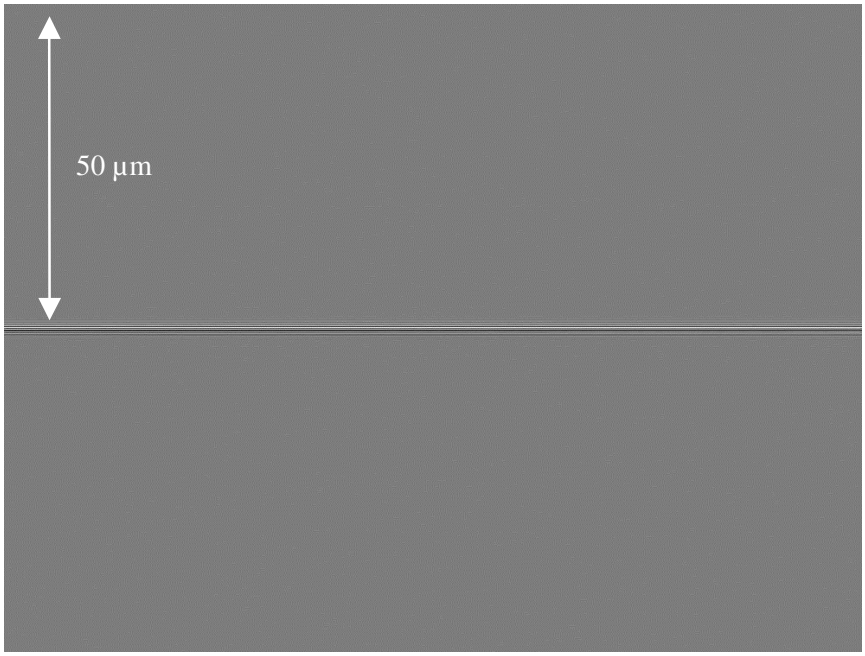

Figure 9 Raw interferogram section obtained on the 2 µm coating (measured using the CSI)

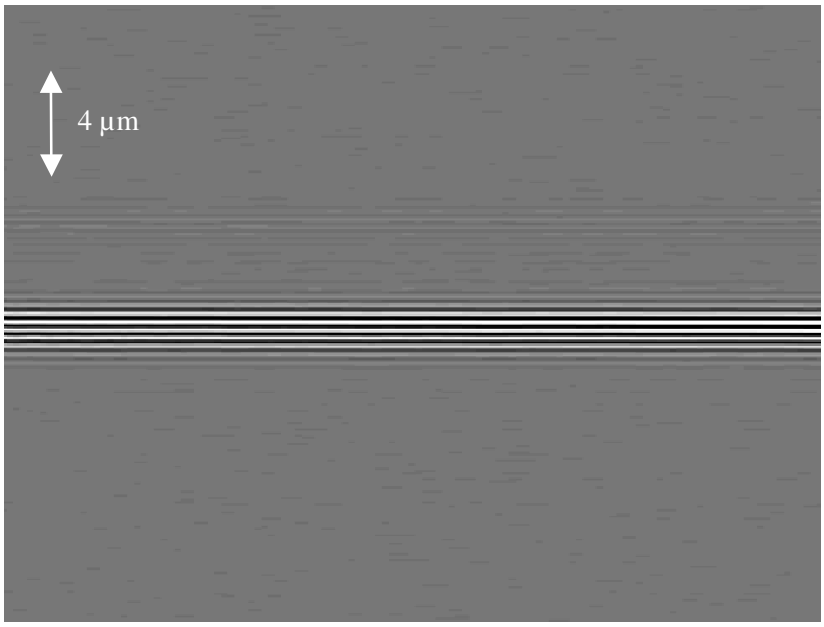

Figure 10 Magnified portion of the centre of Figure 9 (measured using the CSI)

Although the interference signal from the polymer/glass interface is visible in Figure 10 it appears at a distance of approximately 4 µm from the air/polymer signal. There are several reasons for this that will be discussed later.

Further investigation of the 10 µm coating shows that some interference can be seen above the noise floor when the interferogram is filtered such that instrument noise outside the theoretical spectrum is removed. Figure 11 shows a section through the measured interferogram taken from the edge of the slide. In this figure the interference at the far right of the figure is due to the glass/air interface.

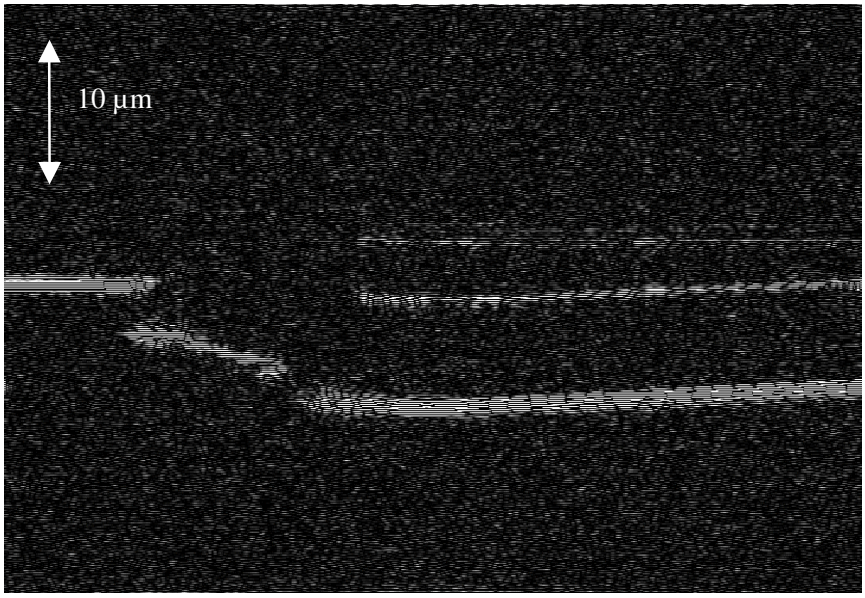

Figure 11 Edge 10 µm coating (filtered) (measured using the CSI)

The polymer surface is the uppermost interference starting on the left of the figure and descending in two steps to the substrate on the right. The interference below the polymer layer is due to the polymer/glass interface. It is noted that this interface is split into two returns one slightly above and the other slightly below, the expected position of the interface. Again, the reasons for this will be discussed later.

A similarly filtered interferogram taken from the HiPER target is shown in Figure 12. The top surface can clearly be seen. Interference from the bottom surface appears approximately 40 µm below the top surface. There is also a very weak interference signal approximately 50 µm below the top surface.

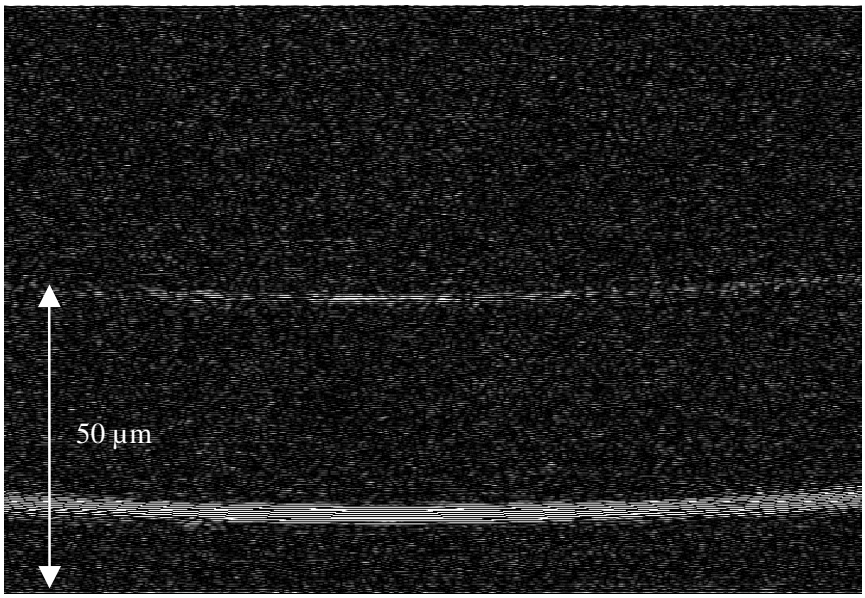

Figure 12 HiPER target (measured using the CSI)

It is noted that the interference from the internal surfaces is considerably less intense than that from the top despite the fact that the intensity reflected from air/polymer and polymer/air interfaces should be equal.

4.2 OCT PERFORMANCE

The OCT system used for this work was a Thorlabs swept source instrument operating at 1325 nm. This instrument is essentially a scanning Michelson interferometer that records the intensity modulation in the interference as the source changes frequency. It can be shown that there is a straightforward Fourier transform relationship between the modulation frequency and path length imbalance in the interferometer. Compared with CSI, OCT has relatively poor lateral resolution (25 µm). The axial resolution depends on the source bandwidth and in this case is specified to be 12 µm (in air).

Figure 13, Figure 14 and Figure 15 show the OCT output for the, 2 µm, 10 µm and 20 µm coatings, respectively.

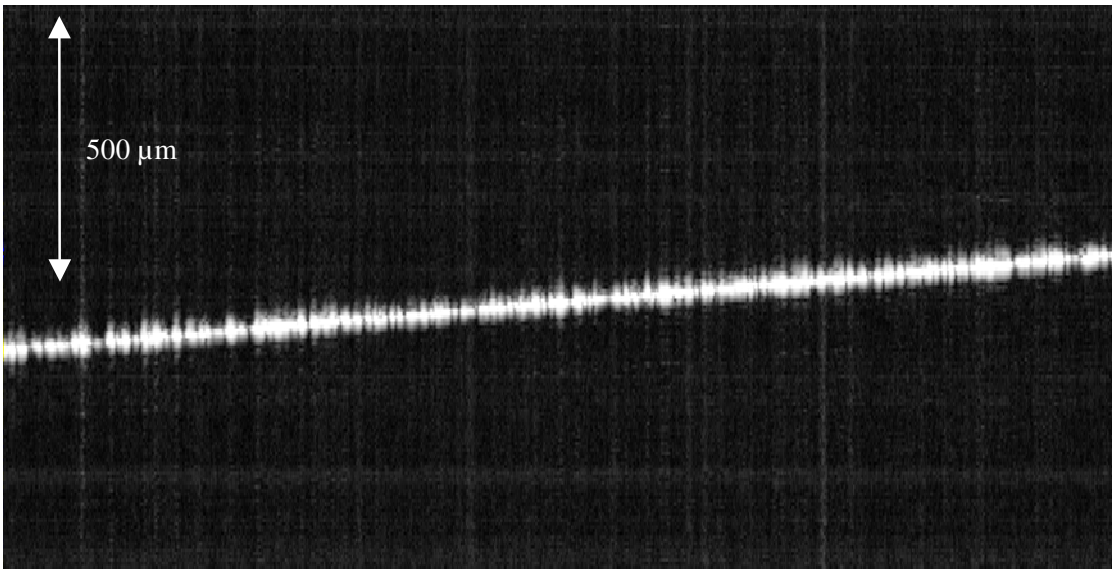

Figure 13 OCT image of the 2 µm coating

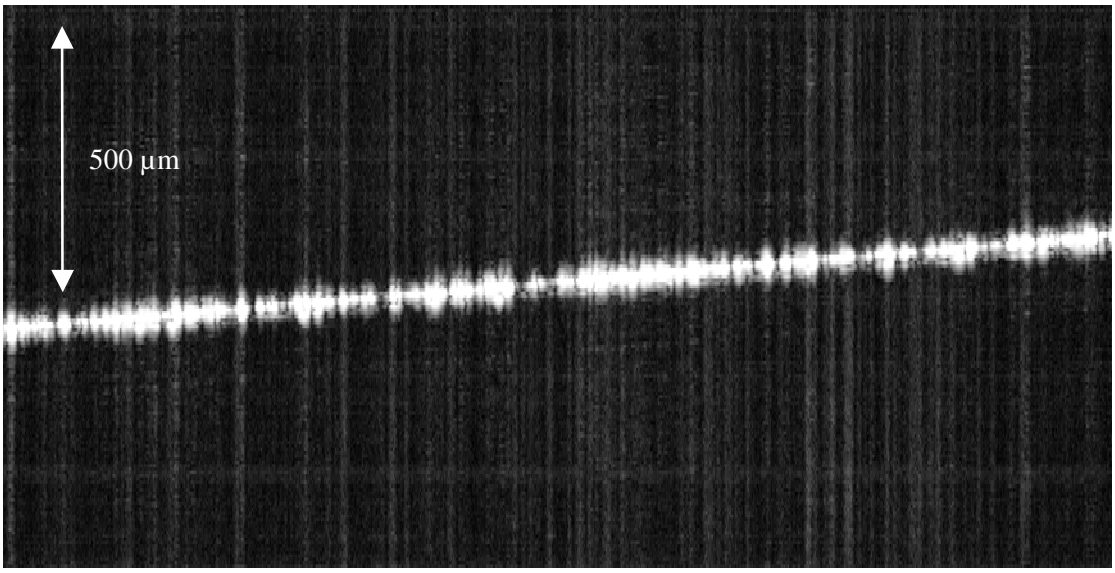

Figure 14 OCT image of the 10 µm coating

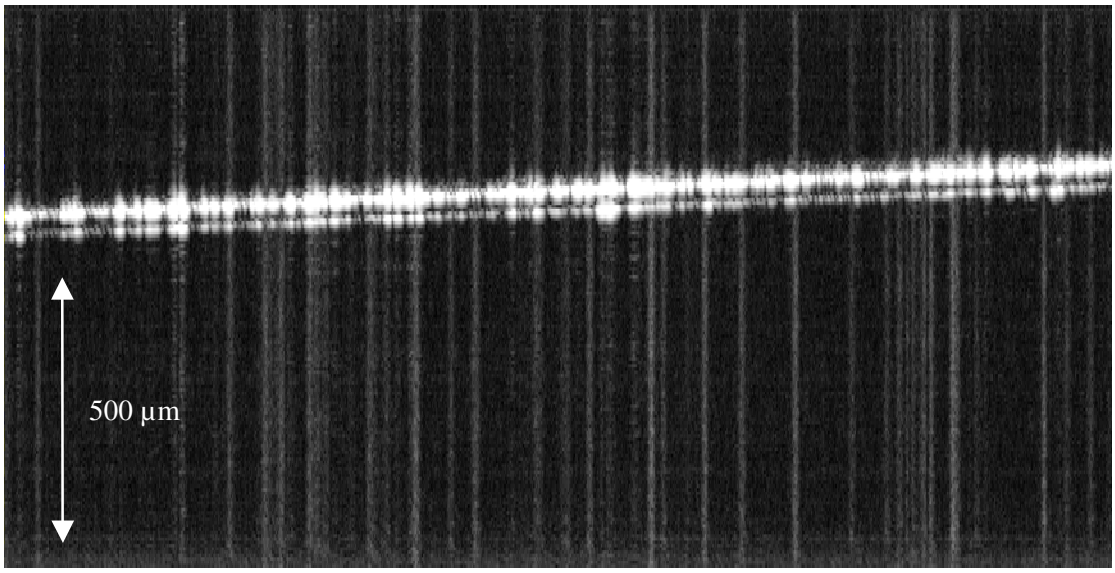

Figure 15 OCT image of the 20 µm coating

It can be seen that there is sufficient signal to identify the polymer/glass interface but the 2 µm coating thickness cannot be resolved. The 10 µm coating is partially resolved (the axial resolution is $12/n$ = 7.5 µm in paralene) and the 20 µm coating is fully resolved by the instrument.

Finally, Figure 16 shows the target imaged by the OCT system. In this case the surfaces are fully resolved. The central line is due to the large specular reflection that was not observed with the tilted glass samples. It is interesting to note the OCT system is optimised for weak non-specular signals (such as those observed in tissue) rather than a specular response, whereas CSI is optimised for specular reflection. It is also interesting to note that only a single response is observed for each surface.

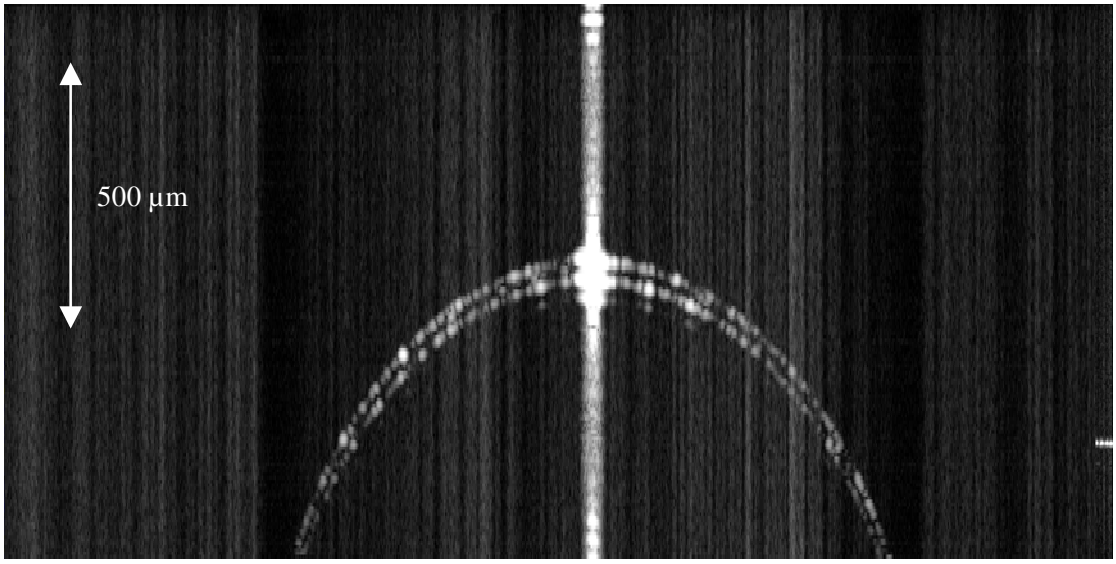

Figure 16 20 µm coating (measured using the OCT)

4.3 DISCUSSION

It can be concluded that both coherence scanning interferometry and OCT are capable of imaging within the layered structures presented. Although the images that are displayed here are qualitative in nature a substantial amount of quantitative information is available. Coherence scanning interferometry can be used to measure the *external* surfaces of the targets and as with regular surfaces this could be achieved to nanometre precision. Care must be taken when measuring the internal surfaces, however.

In fact CSI, OCT and confocal microscopy are very closely related tomographic techniques as we have presented in a recent review article [1]. Confocal microscopy can be considered to derive 3D information from the response of the object to a set of different wavefronts while OCT derives its image from the response to differing frequencies. When using a large numerical aperture objective, CSI uses a combination of both approaches to form an image, and evidence for this is apparent in the results obtained here.

The signals obtained from the OCT system for the case of the 20 µm coating and the target clearly show the internal surface, however, the commercial instrument essentially measures the optical path length along the line of sight and this distorts the image. The optical path length must be divided by the refractive index to give the true path length (so the 20 µm coating appears to be about 32 µm thick). The line of sight will also deviate as it passes through each interface and for this reason the thickness of the target appears to be less at the edges. In addition, we would expect dispersion within the medium to decrease the resolution and to reduce the signal strength, in effect, by spreading the signal slightly.

The CSI instrument has substantially better resolution than the OCT system used in this study but the basis of both techniques are very similar as mentioned previously. It is the large numerical aperture of the CSI instrument that is responsible for its lateral resolution. The large NA is also responsible for the somewhat weaker signals that are observed from the internal surfaces. The fact that a CSI system behaves part as a confocal microscope and part as an OCT system, is apparent in the result from the 10 µm coating (Figure 11). As outlined above, an OCT system measures optical path length and this results in an apparent increase in thickness if not properly accounted for. As Figure 11 shows, this method of measurement also results in a lower interference signal due to the polymer/glass interface. A confocal microscope, however, effectively measures the position of a reflected image of a point-like object. Refraction at the interface causes rays to deviate from and results in the well known foreshortening effect. A confocal microscope will therefore report the layer thickness to be less than it actually is. It is interesting that the degree of foreshortening is also proportional to refractive index and this effect is responsible for the upper interference signal due to the polymer/glass interface in Figure 11. Finally it is noted that, like OCT, refraction at the first interface will further complicate both CSI and confocal microscopy. For the case of a plane surface this interface will cause spherical aberration and result in further foreshortening.

In conclusion, this work shows that standard optical techniques are able to produce 3D measurements of the structures that are of interest to the HiPER project. It is clearly possible to measure the outer surface using either CSI, OCT or confocal microscopy. Of the commercially available methods that were investigated here, CSI will provide marginally better height resolution but slightly less lateral resolution than a high specification confocal microscope.

All the non-contact instruments are capable of providing images of internal surfaces. Of these, OCT provides the most convincing signals providing that surfaces are separated by at least 10 µm (the axial resolution of the instrument). Like confocal microscopy, in its standard form, OCT is not phase sensitive and cannot provide interferometric data. Although this could be implemented in principle, the lateral resolution of this instrument is relatively poor (25 µm) and it is unlikely that inteferometric precision could be obtained, except in the case of near specular reflections from almost flat surfaces, due to speckle noise.

It is evident from this study that refraction (particularly at the air/polymer interface) will confound measurements. Using *a priori* knowledge, however, it is possible to compensate for this in certain cases. For example, for the case of OCT, if the refractive index of the polymer is known, the deviation of the line of sight at the interface can be calculated and the optical path measurement could be corrected to find the true path length. The same basic approach could be used in both CSI and confocal microscopy. It is not possible, however, to completely compensate for this effect using the data collected by standard CSI and confocal instruments and modification, albeit quite slight, is necessary.

CSI makes a coherent recording (*i.e.* interference) and consequently the technique has a distinct advantage over OCT. In order to make quantitative measurements within the coaxial structures that are of interest in the HiPER project, it is proposed that a CSI instrument be adapted to use a modified illumination geometry to allow the confocal and multiple wavelength effects to be separated. Using unambiguous data collection together with careful modelling, interferometric measurement of multiple interfaces between homogenous media is, theoretically, possible.

5 OUTLOOK

5.1 TACTILE

With the development of micro-CMMs, the reliable measurement of spheres with diameters as small as 0.5 mm is now possible. Quantitative measurements of the targets was possible using this micro-CMM technology, but was severely limited by the measurement force of the tactile probe.

Until advances are made in probing technology, it is unlikely that these target measurements will be able to be made using a tactile system. NPL is currently developing a new micro-CMM probe that aims to reduce the measurement force to an acceptable level that will allow highly delicate measurements, such as this, to be made [2].

5.2 OPTICAL

In order to satisfy the requirements of the HiPER project it is necessary to be able to:

i) identify surfaces and
ii) measure their position to interferometric accuracy.

The work discussed in this report shows that currently available optical methods have the capability to identify interfaces between the media even at the relatively low refractive index contrast at the paralene/glass interface. Reliable measurement of internal interfaces, however, is not possible using current instrumentation. Propagation through relatively thin films causes an under-estimate of distance for the case of LSCM and an over-estimate in the case of OCT. For the case of CSI, the interferogram showed a splitting of the surface due to a combination of both of these effects.

It is proposed that a program of work is initiated that comprises of:

i) Modification of a CSI instrument. The illumination used in a standard CSI is a distributed broadband source that is optimal for a single surface. If the aperture of the source is restricted such that the object is illuminated by plane waves the data in the interferogram is separable into its plane wave components. In this form the instrument will behave as an OCT system with a large numerical aperture. The plane wave components can then be propagated through the outer surface to find internal structure.

ii) Data analysis. Using data collected from the modified CSI, the position of the outer layer can be found. Once this surface is known, the individual wave components can be propagated through the interface to determine the internal structure. Inherent in this analysis is compensation for the effects of foreshortening and distortion due to optical path. Recently this approach has been used successfully to image particles within a seeded water droplet from the data within a digital hologram [3].

iii) Component handling. In order to provide data across as much of the surface as possible the pellet should be mounted on a spindle with varying inclination. With these additional degrees of freedom the pellet would be presented to the instrument at different azimuth and elevation angles to cover the surface. If the areas overlap sufficiently it is thought that the measurement redundancy can be used to account for bearing runout and retain interferometric accuracy.

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