DIGITAL HOLOGRAPHY AT LONG-WAVE INFRARED FOR MEASURING THE DEFORMATION OF LARGE SPACE REFLECTORS UNDER THERMAL VACUUM

J.-F. Vandenrijt[(1)], C. Thizy[(1)], Y. Stockman[(1)], P. Queeckers[(2)], F. Dubois[(2)], D. Doyle[(3)], M. Georges[(1)]

[(1)] Centre Spatial de Liège, Université de Liège, Avenue du Pré Aily, 4031 Angleur, Belgium
jfvandenrijt@ulg.ac.be, Cedric.Thizy@ulg.ac.be, ystockman@ulg.ac.be, mgeorges@ulg.ac.be,
[(2)] Microgravity Research Center, Université Libre de Bruxelles, Avenue F.D. Roosevelt 50, 1050 Brussels, Belgium
pqueeck@ulb.ac.be, frdubois@ulb.ac.be
[(3)] ESA-ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
Dominic.Doyle@esa.int

ABSTRACT

Deformation metrology of complex space structures and reflectors is a recurrent problem addressed by ESA. Consequently suitable measurement techniques have to be developed and validated to support relevant on-ground qualification and verification testing.

For that purpose a novel infrared digital holographic interferometer has been developed to measure the deformation of space reflectors without considering specific optical and expensive components such as null lenses.

Laboratory investigations as well as thermal vacuum measurements have been performed to demonstrate the performances of this newly developed interferometer.

1. INTRODUCTION

Holographic techniques in the visible wavelengths are common for measuring the surface displacement of object [1,2]. However the short wavelength induces high stability criteria which are so severe that they often prevent the measurement of large space structures under normal clean room or thermal vacuum test conditions. Additionally in many cases the displacements are too large to be measured by coherent optical techniques employing visible wavelength sources.

To avoid these shortcomings, methods based on structured light illumination like videogrammetry [3], stereocorrelation [3,4], and fringe/pattern projection [3] could be used. In the best case and with a state-of-the-art system, 10 ppm is achievable (i.e. 10 µm on a 1 m wide object). However most often the actually achievable accuracy is likely to be higher and is critically dependent on both the measurement conditions and configuration. These methods also provide a limited number of measurement points.

To fill the gap between visible coherent techniques and structure light techniques, we propose to use holography at a longer wavelength than the usual visible ones, rendering measurements less sensitive to external perturbations and better matching the expected measurement range.

For that purpose we have considered CO_2 lasers emitting at 10.6 µm, in long wavelength infrared (LWIR) spectrum combined with the use of a commercial thermographic camera to design, build and test a novel digital holographic interferometer. An innovative configuration has been selected for measuring deformation of space reflectors without considering specific optics such as null lenses (in the case of parabolic reflector) or complicated and expensive illumination optics (in the case of elliptic ones). It consists in illuminating a diffuser, producing a speckle wavefront which is observed after reflection on the reflector surface. This reflected speckle wavefront behaves exactly as if the reflector was a scattering surface, producing its own speckle, allowing the measurement of its deformation.

Laboratory investigations for validating the technique and determining the measurement uncertainty are presented. A demonstration parabolic reflector is rotated and measured by the new interferometer and compared to measurements of the same surface using another optical measurement method. To perform a representative deformation measurement test of the reflector at cryogenic temperature, a thermal-vacuum test has also been performed on the same parabolic reflector. The results are consistent to the ones of the same reflector obtained with an infrared classical interferometer with null lens, developed earlier at the CSL, and which was used also under similar thermal-vacuum test.

2. TECHNIQUE PRINCIPLE

Speckle interferometry cannot measure the displacement of specular object because it requires the speckle phenomenon which is created by a surface roughness of the order of the wavelength, or higher. For space reflectors, the surface roughness is generally much smaller than 10.6 µm, so they can be considered as perfect mirrors and will not produce any speckle. However Hansen [5] has shown that holography can be used on a specular object. A diffuser being illuminated by a laser produces speckles and a virtual image of this diffuser is observed via the object (see Fig. 1 below). Therefore we see the latter as covered by speckles.

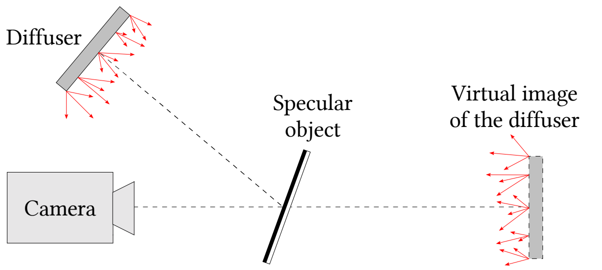


Figure 1. Observation of speckle from a specular object.

3. EXPERIMENTAL VALIDATION

This method was successfully applied by Hansen in visible light for an object of the order of a few centimetres wide [6] by electronic speckle pattern interferometry (ESPI). Here we wish to validate the same principle but applied in LWIR digital holography and for a much larger target. For that purpose we have selected a spare space reflector, representative of ESA reflectors of interest. The latter is shown in Fig. 3 and consist of a parabolic mirror of 1.1 meter diameter and with a focal length of 1.58 meter.

The digital holographic set up used is shown in Fig. 2 below. It is composed of a CO_2 laser from VM-TIM emitting at 10.6 µm at a maximum power of 10 Watts. The laser beam is separated by beamsplitter BS1 into two beams: the object beam (OB) and the reference beam (RB). The object beam illuminates the diffuser D through lens L3. The diffuser is a 10×10 cm² invar plate covered with a scattering powder. The speckle produced by the diffuser is reflected by the reflector and observed by a thermographic camera through the beam combiner BC. This beam combiner is used to superpose the image of the reflector covered with speckle pattern and the RB to create a specklegram. The camera is a VarioCAM from Jenoptik equipped with an uncooled 640×480 pixels micro-bolometer array. For measuring the phase difference, and later calculate the displacement map of the reflector, the mirror MPZT is mounted on a piezo-translator to realise phase-shifting.

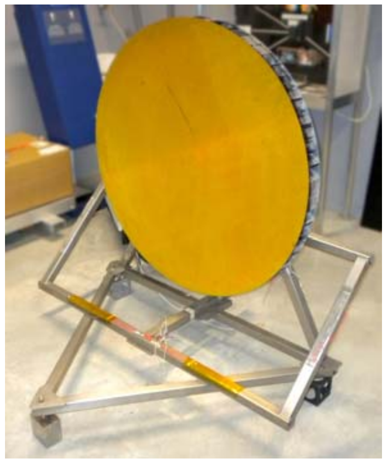


Figure 3. Parabolic reflector used for our investigations.

Fig. 4 shows the phase difference measurement obtained by tilting the reflector, which demonstrates the feasibility of the proposed technique. It is worth noting that for this experiment, the reflector was not mounted on the optical bench but lying on the floor without any damping. This shows the performance of the new interferometer for a non-stable set-up. Those phase differences are processed to obtain the corresponding displacements. Fig. 5 shows the displacements corresponding to the phase difference measured in Fig. 4. To determine the precision of the displacements measured, the reflectors is rotated and measured by the new interferometer and compared to measurements of the same surface using another voptical measurement method. The precision of measurement of HOLODIR is ~ 0.7 µm, with an upper range limit of the order of

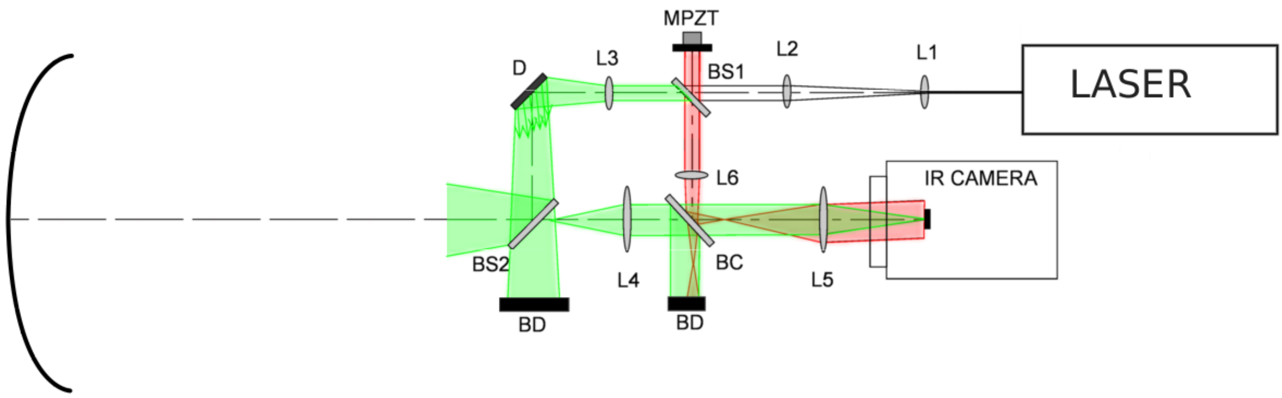


Figure 2. Optical set up used to measure the displacement of the parabolic reflector by ESPI with speckle generated by diffuser.

170 µm between two consecutive acquisitions. This range can be increased by cumulating the measurements, but the measurement uncertainty is also cumulated.

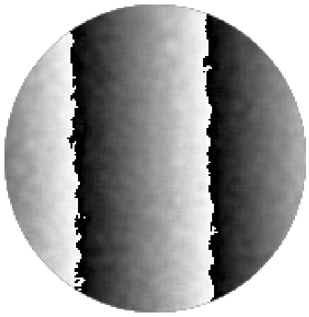


Figure 4. Phase difference measurement for a small tilt of the reflector

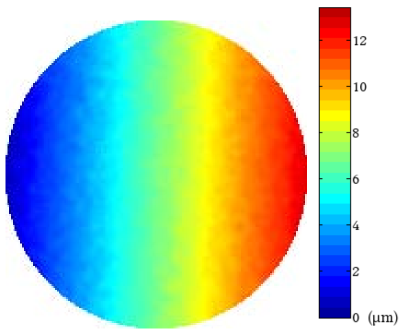


Figure 5. Displacement corresponding to the phase difference from Fig. 4.

4. DEFORMATION MEASUREMENT UNDER THERMAL VACUUM CONDITIONS

Following the laboratory validation, the interferometer has been implemented in a vacuum chamber at the Centre Spatial de Liège (CSL) to measure the deformation of the reflector at cryogenic temperatures. This test is representative of the test realised by ESA for the qualification of space reflectors. This environment is well known for its large vibrations preventing previous tentative of measurement in visible light on the same reflector.

The configuration of the thermal-vacuum test uses the same optical configuration as previously (Fig. 6). However the optical bench has been splitted in two parts. The first part is outside the vacuum chamber, and holds the vacuum incompatible equipments (i.e. the laser and the thermographic camera). The second part inside the chamber holds the interferometer. The separation and combination of the OB and RB beams is realised in the chamber to minimise the impact of differential vibration between the inner and outer bench.

The reflector is placed inside thermal shrouds that are cooled with liquid nitrogen to produce the cold environment. The measurement of the deformation of the reflector for a temperature variation from 288 K down to 113 K is shown at Fig. 8. It has been realised by combining three intermediate measurements, giving an estimated measurement precision of ~ 2 µm.

For validating the performance of the new interferometer, the results obtained have been compared to previous results obtained on the same reflector with a high spatial resolution infrared interferometer, also

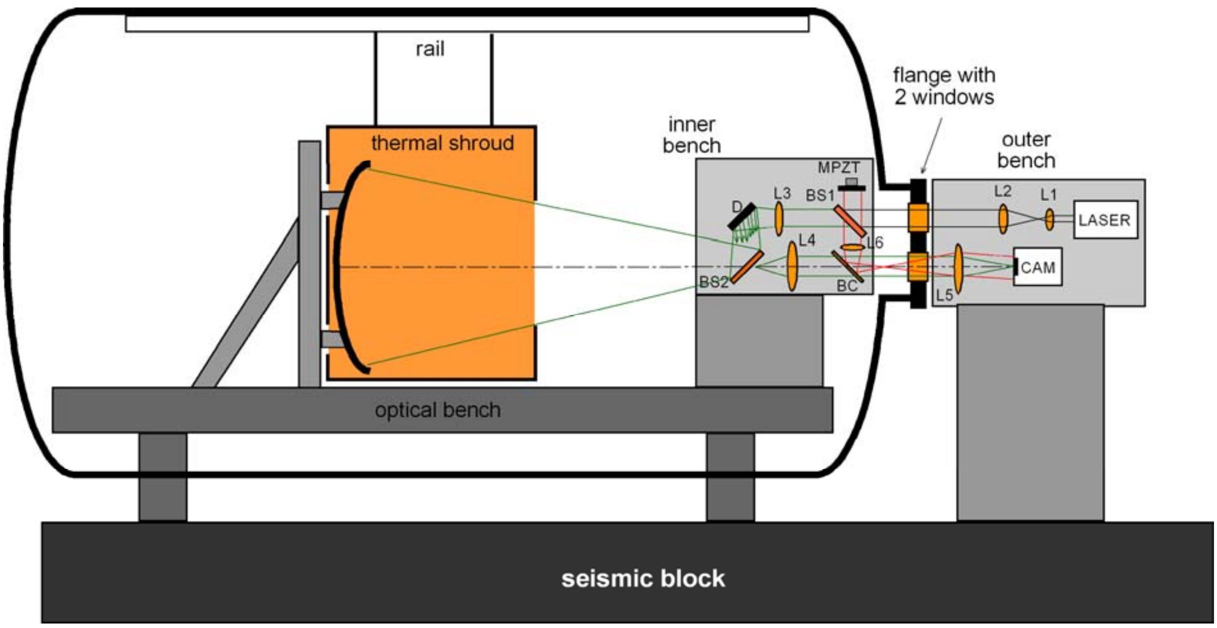
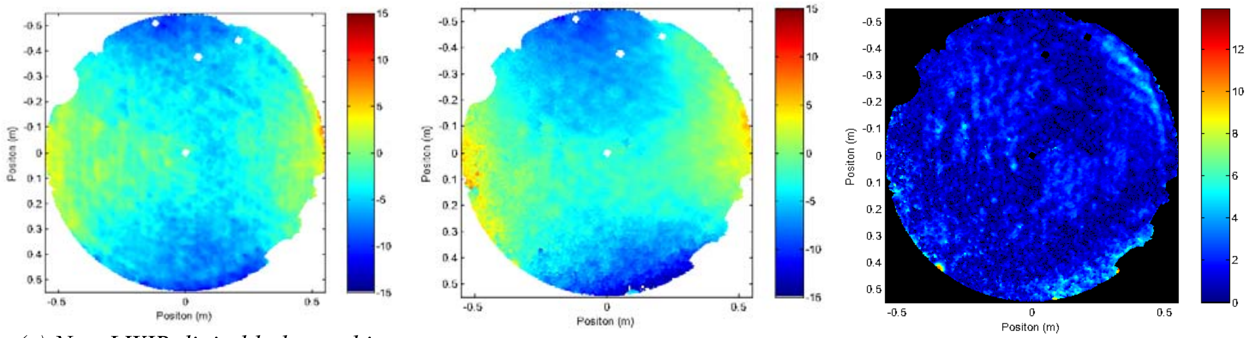


Figure 6. Configuration of the thermal vacuum test.



(a) New LWIR digital holographic interferometer

(b) High spatial resolution infrared interferometer

(c) Difference ~ 1.6 µm RMS

Figure 7. Comparison of the deformation of the reflector for the same temperature variation with a previous results obtained on the same reflector with a high spatial resolution infrared interferometer.

developed at CSL. We compare the deformation measured with the two techniques in Fig. 7 for the same temperature range. The difference between them can be seen in Fig. 7(c). The RMS difference is ~ 1.6 µm, the measurement uncertainty estimated from the first laboratory investigations.

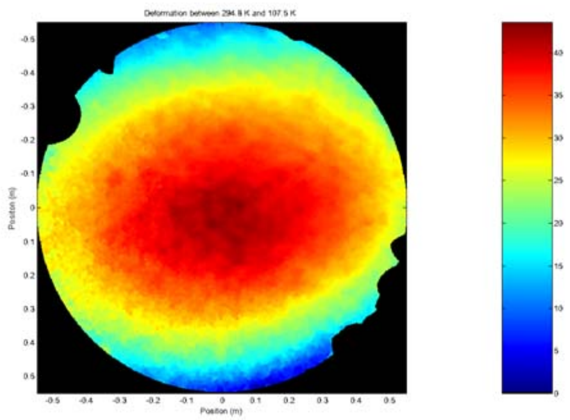


Figure 8. Deformation of the reflector (in µm) at 113 K compared to its shape at 288 K.

5. CONCLUSIONS

In this article, we have shown how to adapt digital holography technique in long-wave infrared for measuring displacements of large space reflectors. This has been possible by using the speckle pattern generated by diffuse illumination. This technique has been experimentally validated with a 1.1 m diameter parabolic reflector in laboratory, and after in representative cryogenic conditions. The needs expressed by ESA have been met in terms of stability and precision of measurements, showing a range starting from around 1 µm up to more than 300 µm. This was realised with using a commercial thermographic camera. No costly specially adapted lenses are required.

The main advantages of the proposed technique come from the longer wavelength, which reduce the stability criteria compared to visible light interferometers, and from the use of a diffuser to illuminate the object, which allows to consider a very large range of reflector shape – the only constraint being the fact that the diffuser imaged by the reflector needs to cover completely the reflector seen from the camera. Thus, this very promising technique makes it possible to consider the measurement of reflectors with a more complex shape that currently start to arise in the industry (e.g. RF antennas).

6. ACKNOWLEDGEMENT

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