Long-wave infrared digital holography for the qualification of large space reflectors

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***Abstract*—Deformation metrology of complex and large space reflectors is a recurrent problem addressed by ESA. The challenging tasks of on-ground qualification and verification testing are to achieve the required accuracy in the measurement of these reflectors deformation and to verify their performance under simulated space conditions (vacuum, low temperature).**

A long-wave infrared digital holographic interferometer for the verification and validation of this type of reflector in a space environment is presented. It has been developed to fill the gap between holography/interferometry techniques in the visible wavelengths and methods based on structured light illumination like videogrammetry, stereocorrelation, and fringe/pattern projection. The former provide a good measurement uncertainty but the displacements are often too large to be measured and they require a very stable environment, while the latter provide large measurement range but with higher measurement uncertainty.

The new instrument is based on digital holography and uses a CO_2 lasers emitting at 10.6 µm combined with a commercial thermographic camera. A diffuser is illuminated by the laser beam, 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 diffusive surface, producing its own speckle, allowing the measurement of its deformation. The advantage of this configuration compared to a classical interferometer working at 10.6 µm, is that it requires no specific optics such as a null lens (in the case of parabola) or expensive illumination/collection optics (in the case of ellipse).

The metrological certification of the system was performed in the laboratory by measuring the tilts of a 1.1 meter diameter parabolic reflector. The displacements are measured in parallel with a Doppler effect interferometer and the measurement uncertainty is estimated. The technique has been certified during a thermal-vacuum test. The deformation of the parabolic reflector is measured for a temperature variation from 288 K down to 113 K. The results are compared to previous results obtained on the same reflector with a high spatial resolution infrared interferometer, also developed at CSL.

Keywords-component; formatting; digital holography; infrared; fullfield

I. 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 achievable accuracy is actually likely to be higher, and is critically dependent on both the measurement conditions and the optical configuration. These methods also provide a limited number of measurement points, because they are not full field measurement techniques.

To fill the gap between visible coherent techniques and structured 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 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 obtained with an infrared classical interferometer with null lens, developed earlier at CSL, and which was used also under similar thermal-vacuum test.

II. 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. As a first step we investigated the performances that could be achieved on rough objects, and showed that when the surface roughness is too low, scattering powder can be applied [5]. 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. But in this case the application of scattering powder cannot be considered. However Hansen [6] has shown that holography can be used on a specular object by the means of a diffuser being illuminated by a laser produces speckles. The virtual image of this diffuser is then observed via the object (see Fig. 1 below). Therefore we see the latter as covered by speckles without any coatings.

III. EXPERIMENTAL VALIDATION

This method was successfully applied by Hansen in visible light for an object of the order of a few centimeters wide [7] measured 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 selected a spare space reflector, representative of ESA reflectors of interest. This is a parabolic mirror of 1.1 meter diameter and with a focal length of 1.58 meter, presented in Fig. 2

The digital holographic set up used is shown in Fig. 3. 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 the 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 realize phase-shifting.

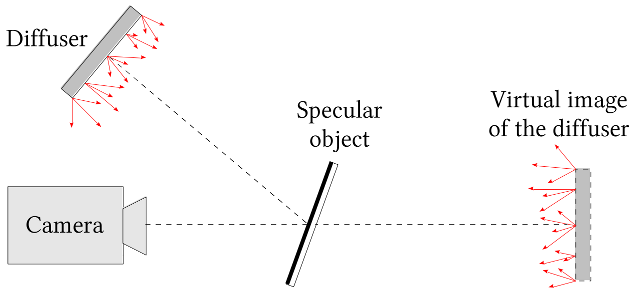

Figure 1. Observation of speckle from a specular object.

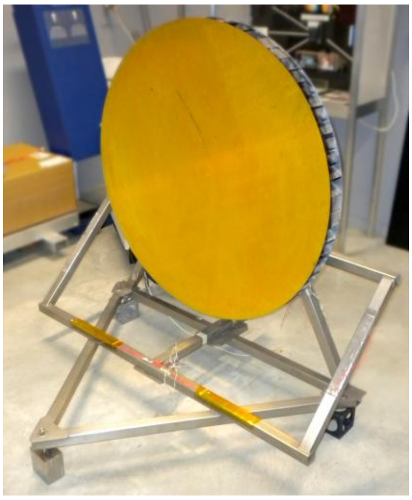
Figure 2. Parabolic reflector used for our investigations.

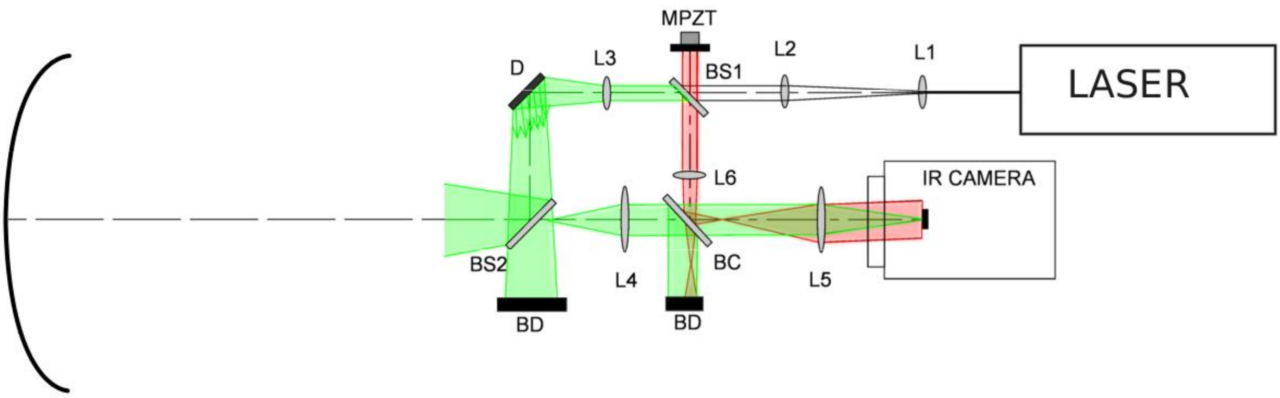

Figure 3. Optical set up used to measure the displacement of the parabolic reflector by digital holography with speckle generated by diffuser.

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 measurement uncertainty, the reflectors is rotated, measured by the new interferometer and compared to measurements of the same displacement using a Doppler effect interferometer. Then we compare both measurements, as shown in Fig.6, which permits us to estimate that the measurement uncertainty is ~ 0.7 µm, with an upper range limit of the order of 170 µm between two consecutive acquisitions. This range can be increased by cumulating the measurements, but the uncertainty of the measurements is also cumulated.

IV. DEFORMATION MEASUREMENT UNDER THERMAL VACUUM CONDITIONS

Following the laboratory validation, the interferometer has been implemented in a vacuum chamber at CSL to measure the deformation of the reflector at cryogenic temperatures. This test is representative of the test realized by ESA for the qualification of space reflectors. This environment is well known for its 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. 7). However the optical bench has been splitted in two parts. The first part is outside the vacuum chamber, and holds the vacuum incompatible equipment (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 realized in the chamber to minimize 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 realized by combining three intermediate measurements and removing the rigid body motion, giving an estimated measurement uncertainty 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 developed at CSL. We compare

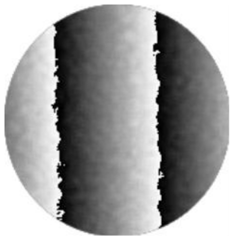

Figure 4. Phase difference measurement for a small tilt of the reflector.

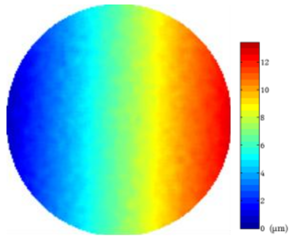

Figure 5. Displacement corresponding to the phase difference from Fig. 4.

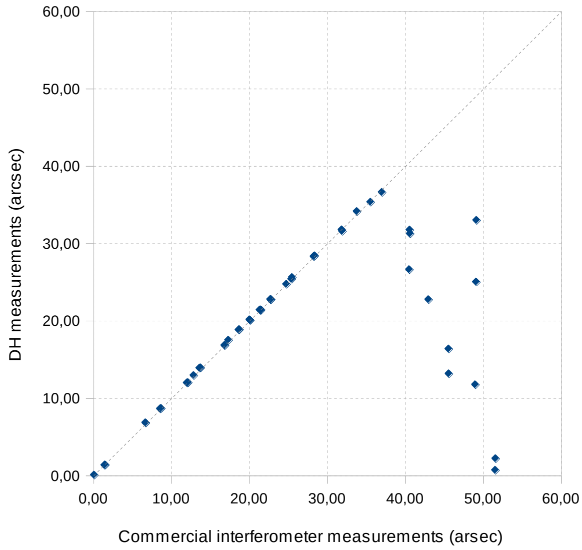

Figure 6. Comparison of the rotation angle measured by the new instrument and the Doppler effect interferometer.

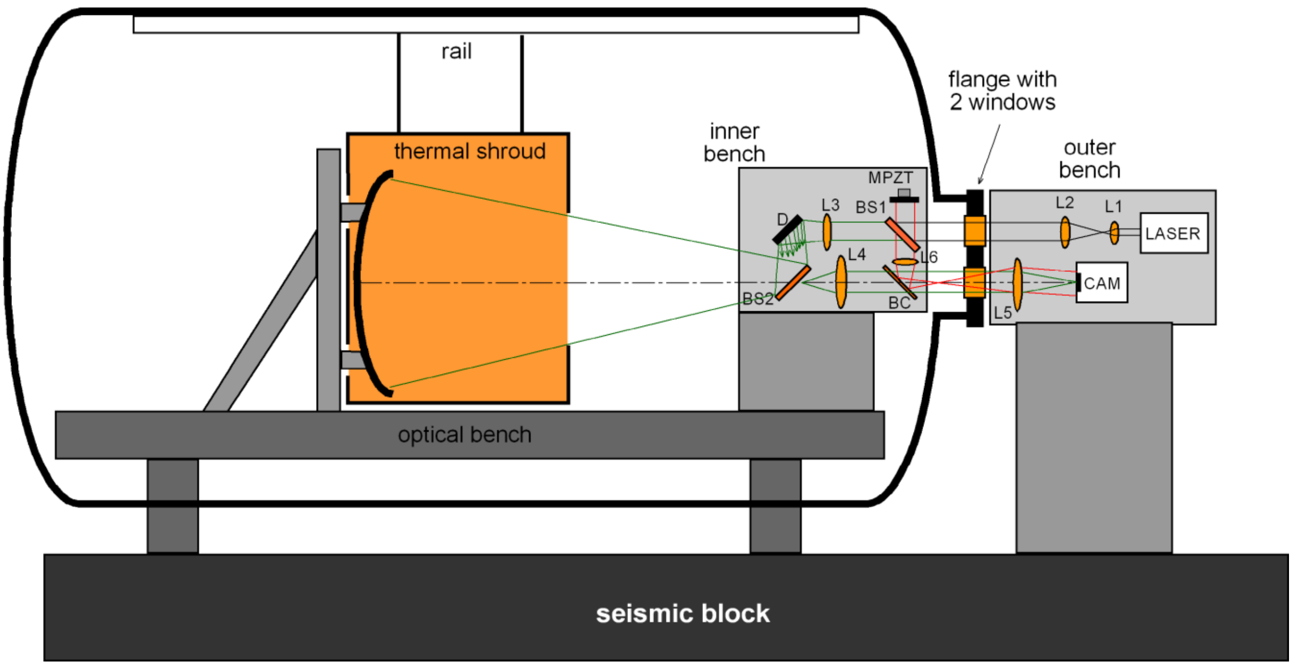

Figure 7. Configuration of the thermal vacuum test.

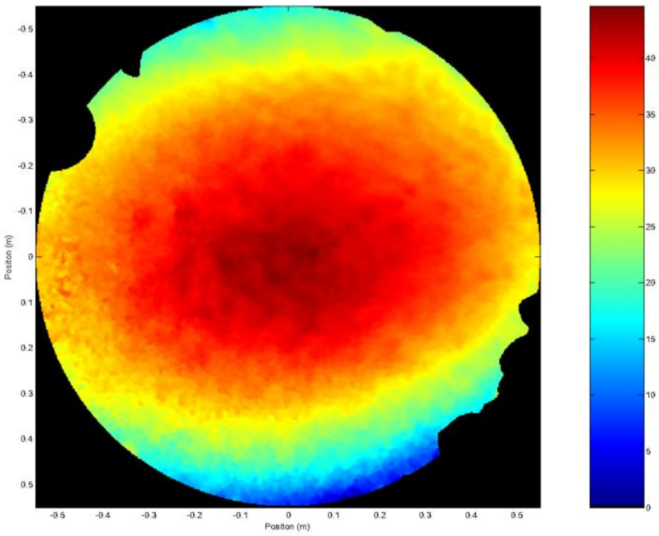

Figure 8. Deformation of the reflector (in micrometer) at 113 K compared to its shape at 288 K.

the deformation measured with the two techniques in Fig. 9 for the same temperature range. The difference between them can be seen in Fig. 9(c). The RMS difference is ~ 1.7 µm, which is compatible with the 2 µm of uncertainty previously estimated.

V. 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 accessible range of measurement starts from around 1 µm up to more than 170 µm. This was realized by 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 reduces 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).

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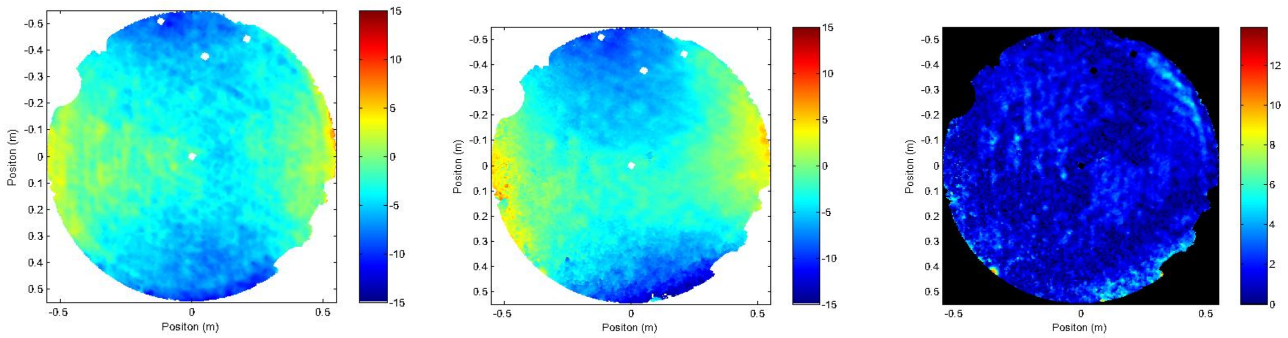

(a) New LWIR digital holographic interferometer

(b) High spatial resolution infrared interferometer

(c) Difference between *a* and *b* ~ 1.7 µm RMS

Figure 9. 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.