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Development of optical ground verification method for µm to sub-mm reflectors

Y. Stockman*, C. Thizy*, P. Lemaire*, M. Georges*, E.Mazy*, A. Mazzoli*, Y. Houbrechts*, P.Rochus*, S Roose*, D. Doyle**, G. Ulbrich**
*Centre Spatial de Liège, Avenue du Pré-Aily, B-4031 Angleur-Liège, Belgium
Tel. +32 4 367 6668, Fax. +32 4 367 5613, Email: ystockman@ulg.ac.be
**ESTEC-European Space Agency, Keplerlaan 1, NL-2200 AG Noordwijk ZH, The Netherlands

ABSTRACT

Large reflectors and antennas for the IR to mm wavelength range are being planned for many Earth observation and astronomical space missions and for commercial communication satellites as well. Scientific observatories require large telescopes with precisely shaped reflectors for collecting the electro-magnetic radiation from faint sources. The challenging tasks of on-ground testing are to achieve the required accuracy in the measurement of the reflector shapes and antenna structures and to verify their performance under simulated space conditions (vacuum, low temperatures). Due to the specific surface characteristics of reflectors operating in these spectral regions, standard optical metrology methods employed in the visible spectrum do not provide useful measurement results.

The current state-of-the-art commercial metrology systems are not able to measure these types of reflectors because they have to face the measurement of shape and waviness over relatively large areas with a large deformation dynamic range and encompassing a wide range of spatial frequencies. 3-D metrology (tactile coordinate measurement) machines are generally used during the manufacturing process. Unfortunately, these instruments cannot be used in the operational environmental conditions of the reflector.

The application of standard visible wavelength interferometric methods is very limited or impossible due to the large relative surface roughnesses involved. A small number of infrared interferometers have been commercially developed over the last 10 years but their applications have also been limited due to poor dynamic range and the restricted spatial resolution of their detectors. These restrictions affect also the surface error slopes that can be captured and makes their application to surfaces manufactured using CRFP honeycomb technologies rather difficult or impossible.

It has therefore been considered essential, from the viewpoint of supporting future ESA exploration missions, to develop and realise suitable verification tools based on infrared interferometry and other optical techniques for testing large reflector structures, telescope configurations and their performances under simulated space conditions.

Two methods and techniques are developed at CSL.

The first one is an IR-phase shifting interferometer with high spatial resolution. This interferometer shall be used specifically for the verification of high precision IR, FIR and sub-mm reflector surfaces and telescopes under both ambient and thermal vacuum conditions.

The second one presented hereafter is a holographic method for relative shape measurement. The holographic solution proposed makes use of a home built vacuum compatible holographic camera that allows displacement measurements from typically 20 nanometres to 25 microns in one shot. An iterative process allows the measurement of a total of up to several mm of deformation. Uniquely the system is designed to measure both specular and diffuse surfaces.

Keywords: optical metrology, holography, IR to sub-mm reflectors, test facility.

1. INTRODUCTION

Space exploration missions like Planck, Herschel (FIRST), Darwin, GAIA and JWST (formerly NGST) require large reflectors that have to be designed to survive space and cryogenic environment. In the frame of commercial communication satellites working in the Ka band frequencies, the reflector surface accuracy and the dimensional stability is critical once in orbit where they have to face the environmental constraints. To qualify these antennas, suitable measurement techniques have to be validated to ensure the good performance of the antenna once in operation.

The first part of this paper reviews the requested performances and constraints of the measurements. Several suitable verification methods and appropriate technologies for testing and surface topography measurement of large reflector structures are presented, and their use under these specific circumstances is analysed. After this trade off analysis, the selected method is presented.

2. MEASUREMENT REQUESTED PERFORMANCE

The selected technique should be able to measure surface deformation larger than 250 microns with an accuracy better than 0.25 µm. The tested reflectors are surfaces with diameters starting from several cm up to 4 m. Their shape can be rotationally symmetric aspheres and conics, concave or convex. Their surface reflectivity is between 10 to 100 % in the visible range, and their microroughness range can be between 0.1 nm up to 1 µm. The fill factor will be as large than 90 % and the sampling distribution does not need to be regular. The system will be able to measure surfaces both at ambient and under vacuum conditions , with the active surface cooled down to 40 K. This means that the access to the optical surface should be limited to avoid thermal leaks. Practically, these requirements are actually not constraining the surface properties, but put serious challenges on the measurement system.

3. TESTING TECHNIQUES FOR REFLECTOR CHARACTERISATION

The selected approach is to start from optical metrology techniques. These are more accurate and generally provide the shape and/or the deformation of the reflector.

These optical metrology techniques are based on a number of fundamental methodologies, namely: Interferometry, Triangulation, 3-D measurements. Eg:

a. 3-D measurements : 3 D metrology machine.

b. Triangulation : theodolite sighting, videogrammetry, stereoscopy…

c. Interferometry measurements : holographic, speckle and Moiré interferometry, fringe projection, Fizeau Interferometer.

Obviously 3-D scanner machines are not compatible with the space or thermal vacuum operational conditions.

A method traditionally used is videogrammetry. The disadvantages of the method are the requirement of having co-operative targets and low accuracy. Accuracy improvements are expected with the use of larger format CCDs (8k by 8k). The technology currently used for such large format CCDs is based on a concatenation of 1k by 1k devices [1]. Videogrammetry does however present certain advantages due to previous experience already gained in applying it in thermal vacuum tests and in-orbit tests using canisters. Literature on this subject is abundant [2][3][4]. The possibility to easily automate the process is also an advantage. The method is not dependent on surface size or distance, or on surface properties (diffuse, edges…) due to the use of targets for measurement point materialisation. One major drawback is ambient light perturbation, but this can be largely solved with flashlights and retro-reflective targets. Videogrammetric measurement systems can be applied in a very large spectrum of configurations, depending on the measured surface, the targets used and the illumination source.

Total station techniques equipped with Distance Measuring Interferometers (DMI) are competitive with videogrammetry. DMI are the most accurate instruments for displacement or length determination. Nevertheless, they require a dual wavelength regime to meet this accuracy (tuneable laser) and an accurate calibration and stability of the wavelength. High accuracy rotational encoders are available for precision angular pointing determination and are probably already military-qualified. Total stations based on DMIs can provide a very good accuracy, low weight system, and insensitivity to background light due to laser use.

What penalises the total station system is: the acquisition time, the spatial sampling requirements and the adaptation of the system to operate under vacuum.

The principle of traditional optical interferometry methods can be adapted to our purpose, by using the operating wavelength of the reflector. Unfortunately, the detector technology is not yet mature. An alternative way and developed at CSL is a High Resolution Infra Red Interferometer. Commercial IR interferometers are limited by the IR camera resolution. At CSL this limitation is bypassed by using a QWIP detector 640 X 512 pixels operating in the wavelength band between 8 and 9.5 µm.

However, the major drawbacks of these interferometric methods are the need for a corrector (compensating optic in order to work in stigmatic configuration). Large slopes impose also to use large optics and calibration process.

Using holographic interferometry can circumvent the auxiliary optics limitation. It provides also a backup solution. The major drawbacks of the "standard" holographic method are: no absolute measurement, high accuracy implying good stability, and the difficulty to measure high local slope deformations e.g. print through in honeycomb reflectors, discontinuities. However, the absolute shape is determined during the manufacturing process, the stability problems are solved by using vacuum optical bench and short exposure time, and the fast local slope deformations are linked to thermal effects that are generally a slow process. The iterative proposed process insures large deformations, so that there is theoretically no limit. Practical cases [6] have already demonstrated that deformation up to 2000 µm can be measured.

Additionally to its accuracy and range, the method presents the advantage that it is readily adaptable for use in vacuum testing conditions. It needs only 1 or 2 small holes in the thermal shrouds. It is a non-destructive technique (there are no intrusive targets required for either specular or diffuse reflectors).

4. HOLOGRAPHIC CAMERA TECHNIQUE

4.1 Introduction

The holographic camera allows displacements measurement from typically 20 nanometers to 25 microns in one shot. A hologram is recorded when the object is at rest. The object is progressively displaced/deformed and the hologram is readout. If the object is illuminated during the hologram readout, one observes an interference pattern (interferogram) of the optical phase difference due to the surface displacement. Due to the geometry of object illumination and observation, these displacements are measured out-of-plane. The analysis of interferograms can be achieved by any of the classical technique described in the literature. A unique feature of the CSL holographic camera [7] is that it uses a photorefractive crystal to record the hologram. The latter allows in-situ recording of the hologram and is fully erasable by the readout beam itself. This means that once the hologram is readout (and the interferogram digitised by a frame grabber), it is erased and no longer available. The holographic camera is then ready for a new measurement process (hologram recording + readout).

4.2 Breadboard configuration and results

Our first concern is to validate the holographic camera for the measurement of specular surfaces. Previous applications always used diffusing surfaces or the surfaces were white painted [6]. To overcome this problem a diffuser is introduced in front of the camera. This collects the light from the mirror and scatters it to the holographic camera. In the breadboard configuration (Fig 1) a simple spherical mirror (f/10) is used to demonstrate the concept.

The Nd-YAG laser delivers a 500 mW beam that is coupled into an optical fiber that bring the light to the holographic camera in a flexible way. This optical fiber allows the holographic camera to be used at some distance (several meters) from the laser source.

An electronic shutter permits control of the illumination of the set-up. The first time to take the reference hologram and then at each required subsequent time versus the deformation or the temperature.

The spherical mirror is mounted on a translation stage to allow defocus. It can also be tilted (around Y and Z axis). The diffuser is mounted on three translation stages corresponding to the three translations along X, Y and Z. The microscope objective is selected to illuminate correctly the tested mirror and is placed close to the focal plane of this latter one. A beam splitter is used to separate the illumination beam from the reflected signal beam. It is demonstrated that this beam splitter is not mandatory and that the illumination optic can be placed close to the diffuser (see Fig 8 : Certification test layout).

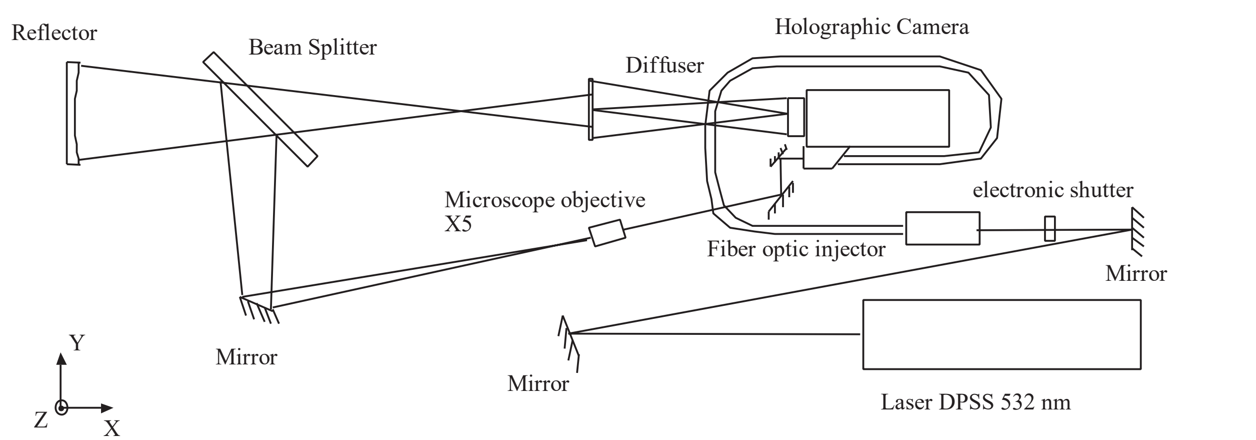

Fig 1 : Scheme of the experiment for the observation of a spherical mirror displacement with the holographic camera.

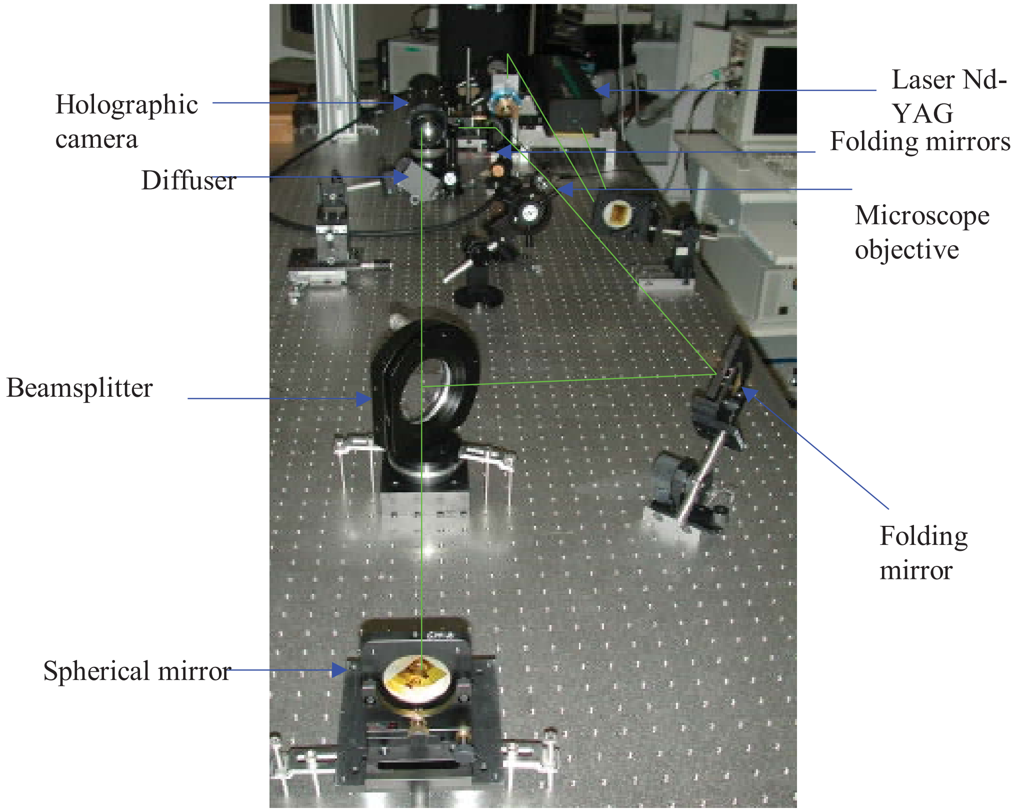

Fig 2 : Picture of the Breadboard experiment

The set-up has been modelled in ASAP software. The recorded holograms are compared to the simulation and to directly measured values of tilt. An autocollimator records the F/10 spherical mirror tilt angles via a flat mirror fixed at the rear side of this mirror. A difference of 20 nm RMS is recorded between the two systems whatever the tilts are within the fringe resolution of the camera. This is in agreement with the experimental error budget. The iterative process is also demonstrated. The principle is that once too many fringes are present in the interferogram due to the displacement, a new reference is taken.

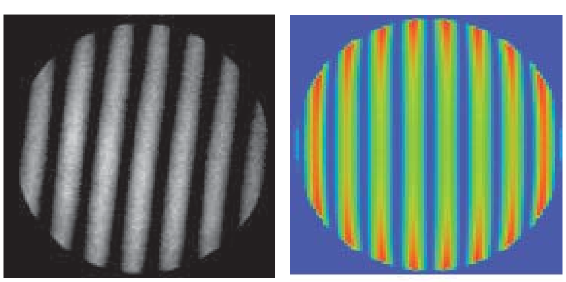

Fig 3 : Interferograms of the spherical mirror tilted observed by the holographic camera using an intermediary diffuser (left) and simulated (right)

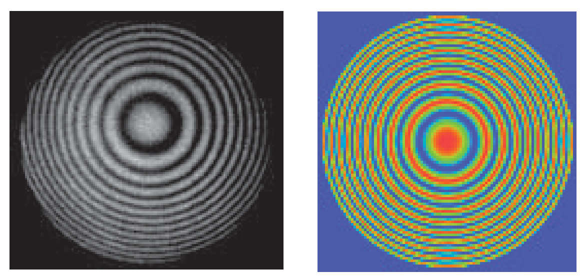

Fig 4 : Interferograms of the spherical mirror defocused observed by the holographic camera using an intermediary diffuser (left) and simulated (right)

Large tilts equivalent to several 10s of µm displacements have be carried out. The measured difference was within 100 nm PTV. The graph of Fig 5 indicates the deviation between displacement recorded with the holographic system and the one measured with a commercial interferometer.

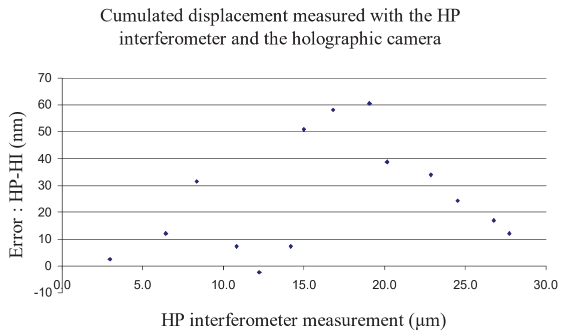

Fig 5 : Holographic camera calibration with a commercial interferometer of displacement of several tenth of µm.

An important point with the new configuration is the orientation of the sensitivity vector in order to ensure a proper calculation of the displacement at the level of the object from the measurement done on the diffuser. It appears that this configuration is the most sensitive one, in the sense that the illumination and observation points are both along the optical axis of the camera.

The impact of the diffuser position is evaluated with this breadboard. Indeed, the simulation shows that the fringe contrast and shape change with respect to the diffuser position for a non-stigmatic configuration. It appears that it is mandatory that the diffuser position must be far away [5] from the aberration area to get correct data. The further we are, the better the fringe contrast is. But the set-up becomes longer and the diffuser diameter increases (Fig 6), so that a trade off must be done.

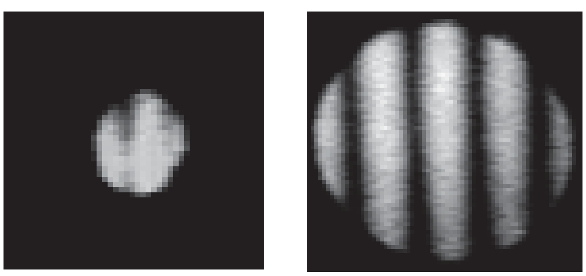

Fig 6 : Impact on the fringe contrast versus the diffuser position for tilt. In the left image the diffuser is at 100 mm from the best focus once for the right image it is at 300 mm.

The diffuser characteristics are not critical. Five-glass plates have been polished with 5 different grain sizes ranging from 10 to 75 µm. Despite the different transmitted intensities the quality of the interferogram is not degraded. Interferogram quality principally depends on the object beam intensity and the quality of the recording.

A critical issue is the mechanical stability of the set-up. Fig 7 shows the impact of diffuser displacement along an axis perpendicular to the optical axis on the measurement of the displacement of a spherical mirror. The translation along the optical axis is less critical than in-plane translation. Typically, the diffuser can undergo a vibration along the optical axis of roughly 200 µm, while in-plane translation the maximum displacement is 10 µm (see Fig 7) whatever the diffuser characteristics are. Above these limits, the phase image is poor and cannot be unwrapped. These limits must anyway be considered carefully. Indeed, despite the fact that the fringe amplitude is still large when the diffuser moves at these limits, because the diffuser movement introduces speckle decorrelation, the phase image is degraded but can still be unwrapped.

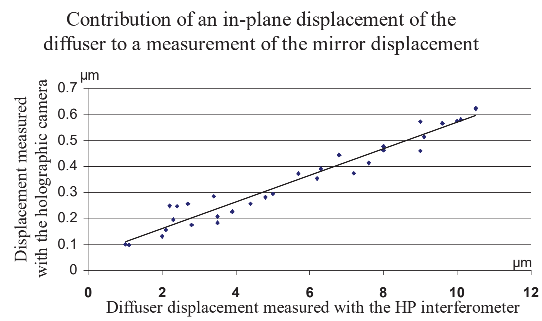

Fig 7 : Contribution of diffusers displacement in plane to the measured displacement of the mirror.

4.3 Application to practical case

The breadboard configuration is close to a stigmatic one. When working with other quadrics and avoiding correctors, the configurations are not necessarily stigmatic. Fortunately, it has been demonstrated by simulation that the method can work in non-stigmatic configuration and without a null lens. For example, in the case of a parabolic reflector, the source is at the centre of curvature, and the collecting diffuser is several cm away. This is proved with the breadboard on which the illumination microscope objective is not placed accurately at the curvature centre of the spherical mirror. To practically certify the method, a 1.1 m diameter F/2.8 CFRP gold coated parabola will be used. This parabola has been introduced in the simulations. These show that:

1) the diffuser position has to be out of the caustic area to achieve correct fringe contrast . This is in accordance with [5], where it is required to be at 3 times $L = cc*1/R*(\text{semi- Aperture})^2$. For the proposed configuration the conic constant cc is -1, the radius R 3160 mm and semi aperture 550 mm. This gives for 3*L, 287 mm.

2) the requirement on the source and reflector stabilities between two holographic acquisitions is acceptable (few microns). But care should be taken in the design of the supports and it is essential to perform the measurement on a single optical bench.
3) the initial position of the source allows errors larger than +/- 50 mm. This means that an accurate initial alignment is not required. Mechanical positioning should be sufficient. However, if the set-up is far away from the optimum configuration, the aberration will be large and it will be required to move the diffuser away from the mirror. For a 50 mm alignment error, the diffuser should be 2 times the distance as for a correct alignment.
4) It is possible to recover the deformation from the fringe interpretation.

All these points are confirmed with the breadboard.

4.4 Deformation processing and accuracy measurement

Since the holographic system is a sequential process: large deformations are achieved by the accumulation of small deformation measurements. If the reflector is a diffusing surface, the same algorithm as in [6] can be used. If the surface is reflective, a data handling close to traditional interferometry can be used.

The major steps are :

1. Record the fringe pattern
2. Perform phase calculation
3. Unwrap the phase
4. Zernike polynomial fitting

The evaluation of this data handling process is demonstrated with the results achieved during the IR (10.59 µm) interferometric measurement performed on the CFRP antenna. It comes out that the algorithm residual error is less than 20 nm. Taking into account the instrumental error, it is expected to achieve an accuracy better than 100 nm.

Tests with the breadboard demonstrate that these accuracies level are easily achieved (20 nm error for a tilt), unfortunately, it is necessary to mention that breadboard environmental conditions are favourable. To confirm the performance of the system, a certification test is planned under representative thermal vacuum conditions.

5. CERTIFICATION

Both developed instruments (Vacuum Holographic camera and High Resolution IR interferometer) will be certified on a practical case to check the robustness and operationality of the instruments. The proposed test configuration is similar for both experiments and is presented in Fig 8.

The tested item is a CFRP reflector already described that will be cooled down to 40 K via liquid He cooled shrouds. The certification will be done by intercomparison between both methods. In case of discrepancies, the data will be compared to a previous test performed with a commercial IR interferometer.

The reflector is inside the shrouds and fixed to a corner plate. Three large stands support the holographic camera, the diffuser and the illumination optic. None of these supports require accurate adjustment but they need to be mechanically stable.

The diffuser is a simple ground glass plate without any particular optical quality in terms of microroughness or homogeneity. The criticality is the variation of these properties between acquisitions. Care has to be taken about the diffuser mechanical and thermal stability.

The illumination optics is a standard microscope lens that must be vacuum compatible. Since it is close to the thermal shrouds, its thermal isolation or regulation has to be considered. It is possible to put it far away from the thermal shroud but this will increase the hole in the shroud, which is not optimum for the thermal configuration. The holographic camera has been adapted to be vacuum compatible. The laser source is outside the chamber and the light is coupled via a fiber. A dedicated development was under taken for the vacuum feed through of this optical fiber since. The only additional feedthrough is the electrical one to supply and carry out the camera signals.

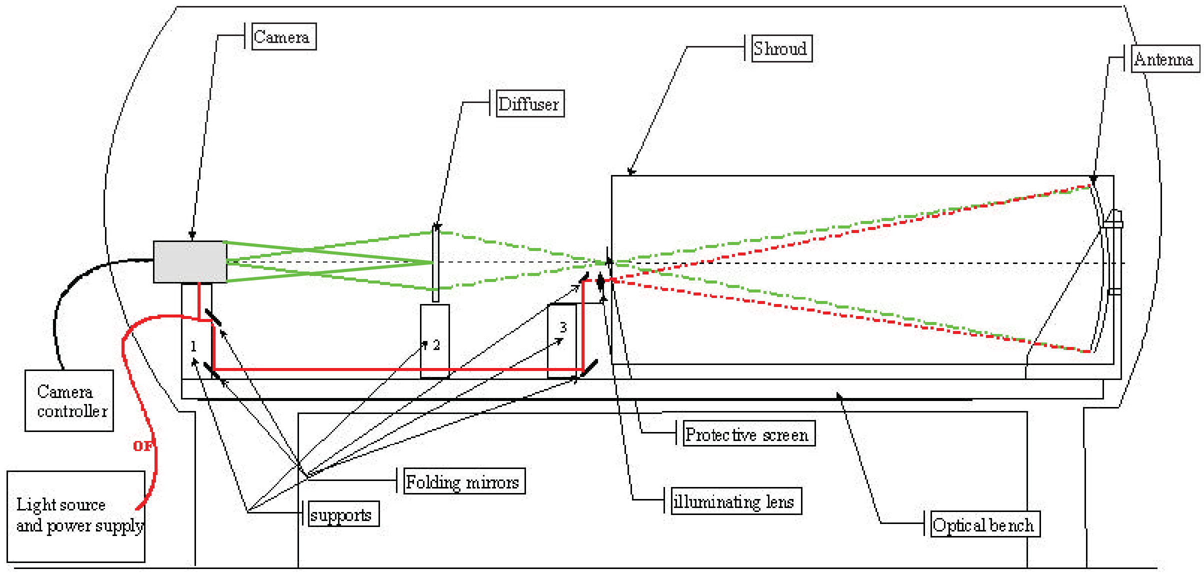

Fig 8 : Certification test layout

6. CONCLUSION AND FURTHER DEVELOPMENTS

The holographic technique has already demonstrated that it is a well-suited method to test large deformations (2000 µm) on reflectors with a very good accuracy (0.2 µm). The presented method demonstrates that the technique can be used with specularly reflective surfaces and that the expected accuracy should be 0.1 µm theoretically for several mm deformation ranges. The method presents many advantages for thermal vacuum reflector deformation measurements, the most important being its simplicity to set up. Indeed, no motorised units are required for adjustment or alignment and no calibration is needed as in traditional interferometry methods. However, since it is a sensitive method, adequate thermo-mechanical stability is mandatory.

6.1 Further developments

In the near future, it is proposed to replace the present crystal of the holographic camera by a CdTe crystal. These have better diffraction efficiency and are near IR sensitive, so that the fundamental line of Nd-Yag laser or an IR laser diode can be employed. The use of a NIR band allows further compaction of the set-up and a reduction in the mechanical stability requirements.

7. ACKNOWLEDGEMENTS

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