Performances of NIR VPHGs at cryogenic temperatures

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ABSTRACT

We summarize the performances measured at room temperature and in cryogenic conditions of a set of NIR Volume Phase Holographic Gratings (VPHGs) which can then be used in astronomical instrumentations. VPHGs are novel optical components which can replace standard transmission gratings. Instead of a surface modulation a diffraction index modulation printed in a volume of material generates the diffraction according to the required specifications. Results on transmission and wavefront deformation are presented and compared in the two temperature regimes. These results were achieved along the run of the Joint Research Action 6 of OPTICON FP6 programme whose participating institutions are Osservatorio Astronomico di Brera (INAF), Instituto de Astrofísica de Canarias, Centre Spatial de Liège, Politecnico di Milano and European Southern Observatory.

Keywords: VPHG, cryogenic, NIR

1. INTRODUCTION

Modern astrophysics can only be understood in terms of the constant development of the most powerful telescopes and instrumentation that make possible the observation of ever more distant objects, or that provide a notable improvement in the body of data for already known objects, by means of greater spatial resolution and sensitivity, and new modes of observation that new instruments offer in combination with ever larger telescopes with better image quality. There is currently much activity in this field of observational astronomy with the recent coming into service of a battery of large (8–10 m) telescopes equipped with latest-generation instrumentation and the huge effort now being dedicated to future ELTs (Extremely Large Telescopes), with project currently under way on both sides of the Atlantic. In all these projects, spectrographic-type instruments, both simple and integral field and operating in the near and/or mid-infrared, are now, or soon will be, workhorses common-user instrumentation. All these instruments try to combine a wide field of view with a high spatial resolution capability. This leads unavoidably to the use of dispersive elements of great size and complexity of manufacture, quite apart from the high economic cost.

VPH gratings [1,2,3,4] are commonly used in Raman spectroscopy [5] and have been in use in astronomy from about 2001 as an interesting alternative to traditional diffraction gratings.and grisms in latest-generation astronomical instrumentation. Among others, there are a few characteristics of VPHs that make them suitable for use in astronomy: high diffraction efficiency near the blaze wavelength; adequate wavefront transmission; high reproducibility and reasonable cost. However, VPH gratings to date have not been designed and built to be cooled to cryogenic temperatures for their mounting in astronomical IR instrumentation. In this project, we aim to perform the optical characterization of an array of VPH gratings, designed and built under the OPTICON FP6 JRA6 cooperative scheme, to operate in the near-infrared wavelength range at cryogenic temperatures. In this contribution, we deal specifically with measurement of the grating transmission at ambient and cryogenic temperatures in order to determine first of all the operability of the gratings when cooled and then to estimate the differences in behaviour in the diffraction produced by the gratings in both cases. We have also measured the deformation of the wavefront induced by the gratings in the light beam that passes through them to estimate the difference in behaviour at the two temperatures. The latter has been measured independently by the IAC and the CSL teams, using similar experimental setups.

The gratings used along this project are optimized for use in the near infrared (J, H and K bands) and fabricated using dichromated gelatine technology [6]. In Table 1 are listed the design specifications of the gratings which have been manufactured at CSL.

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Table 1. VPHG prototypes specifications.

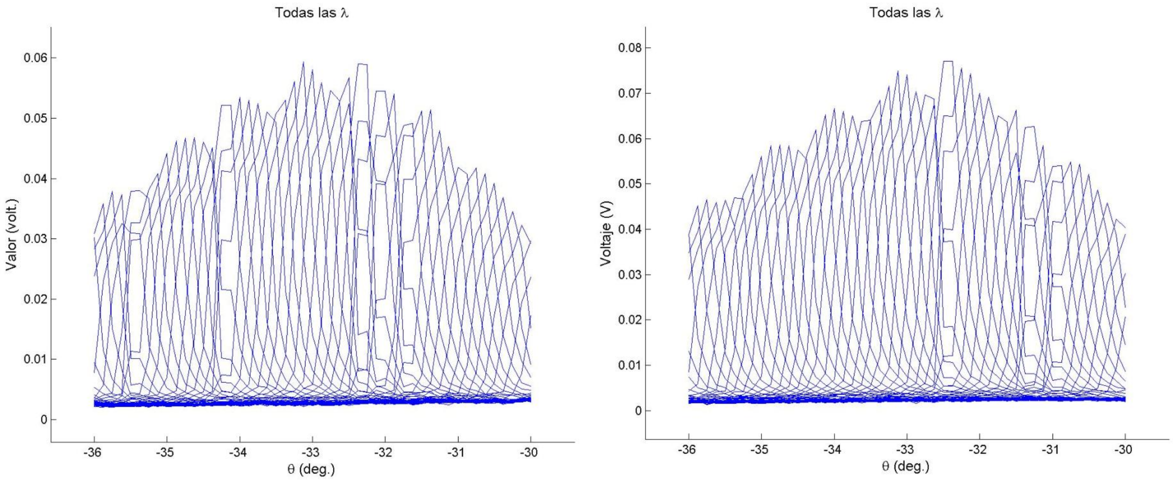
Laboratory Prototype IR-J1	
Substrate material:	IR-Fused silica.
Substrate dimensions:	46 x 46 x 10 mm
Clear aperture:	∅35 mm
Line density:	1156. 78
Operating range:	1100 – 1400 nm
Efficiency:	>40% at 1100 nm >90% at 1250 nm >40% at 1400 nm
AR Coatings:	none
Wavefront error:	λ/2
Laboratory Prototype IR-H1	
Substrate material:	IR-Fused silica.
Substrate dimensions:	46 x 46 x 10 mm
Clear aperture:	∅35 mm
Line density:	867. 52
Operating range:	1500 – 1800 nm
Efficiency:	>50% at 1500 nm >90% at 1650 nm >40% at 1800 nm
AR Coatings:	none
Wavefront error:	λ/2
Laboratory Prototype IR-K1	
Substrate material:	IR-Fused silica.
Substrate dimensions:	46 x 46 x 10 mm
Clear aperture:	∅35 mm
Line density:	646. 68
Operating range:	2000 – 2400 nm
Efficiency:	>50% at 2000 nm >90% at 2200 nm >40% at 2400 nm
AR Coatings:	none
Wavefront error:	λ/2

2. MEASUREMENT OF TRANSMISSION

In this section we examine how the VPH grating transmission varies as they pass from ambient to cryogenic temperatures. In order to carry out these measurements we have arranged a setup comprising a halogen lamp, a spectroradiometer, a cryostat with temperature sensors, a rotator, and lenses and mirrors to direct, collimate and focus the light.

The gratings were measured both at ambient and cryogenic temperatures, in the range of 150K. A graphical summary of the results are shown in the following figures corresponding to each of the grating prototypes:

- VPHG J1a: figures 1 and 2.
- VPHG J1b: figures 3 and 4.
- VPHG H1a: figures 5 and 6.
- VPHG H1b: figures 7 and 8.
- VPHG K1a: figures 9 and 10.


Todas las λ

Todas las λ

Fig. 1 VPHG J1a. Composite plots showing the transmission graphs for each wavelength by scanning the whole angular range. The grating transmission would be the top envelope of the graphs. Left panel shows the RT measurement. Right panel, the cryogenic one.

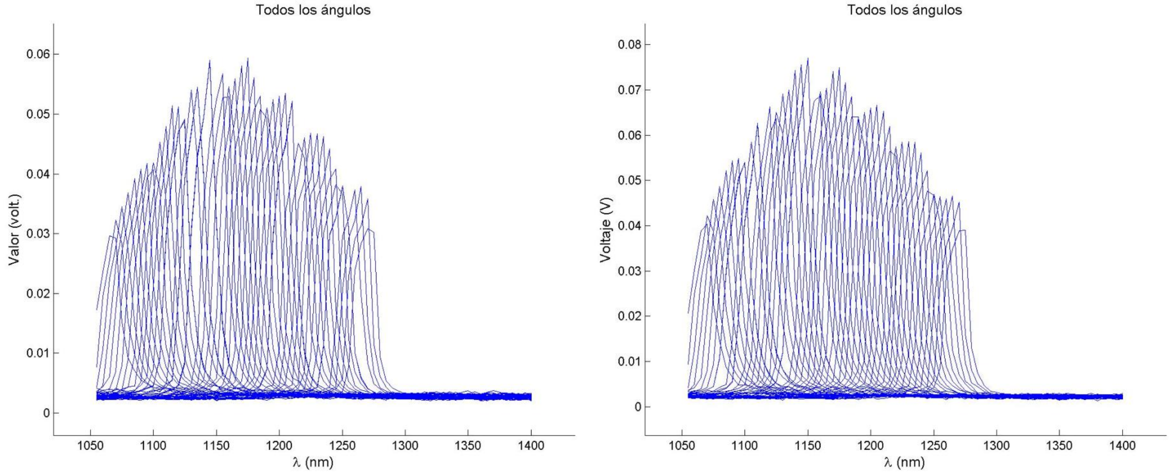

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Fig. 2 VPHG J1a. As in figure 1, but interchanging the parameters. The scan runs through wavelengths and each angle is depicted. Left panel shows the RT measurement. Right panel, the cryogenic one.

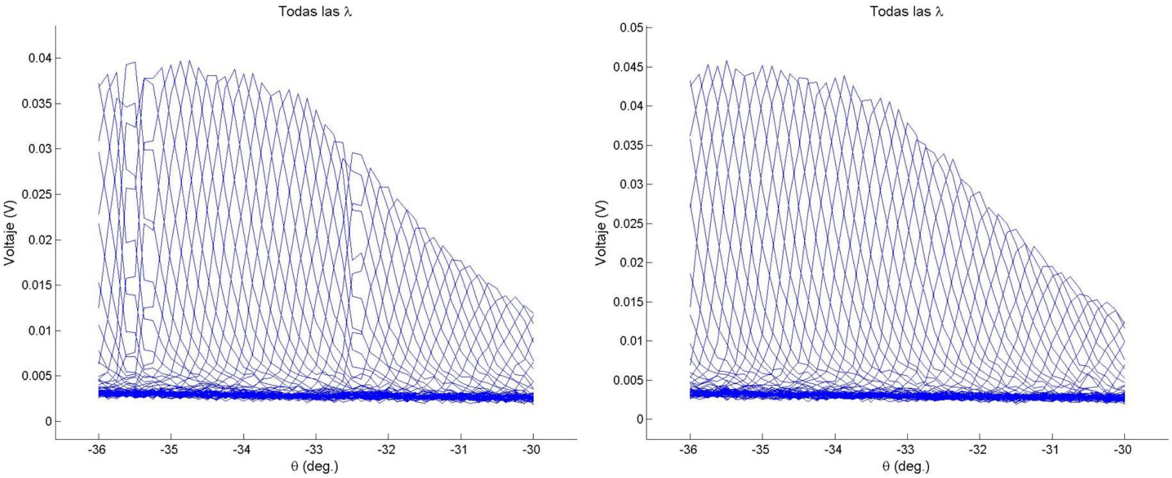
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Fig. 3 VPHG J1b. As in figure 1.

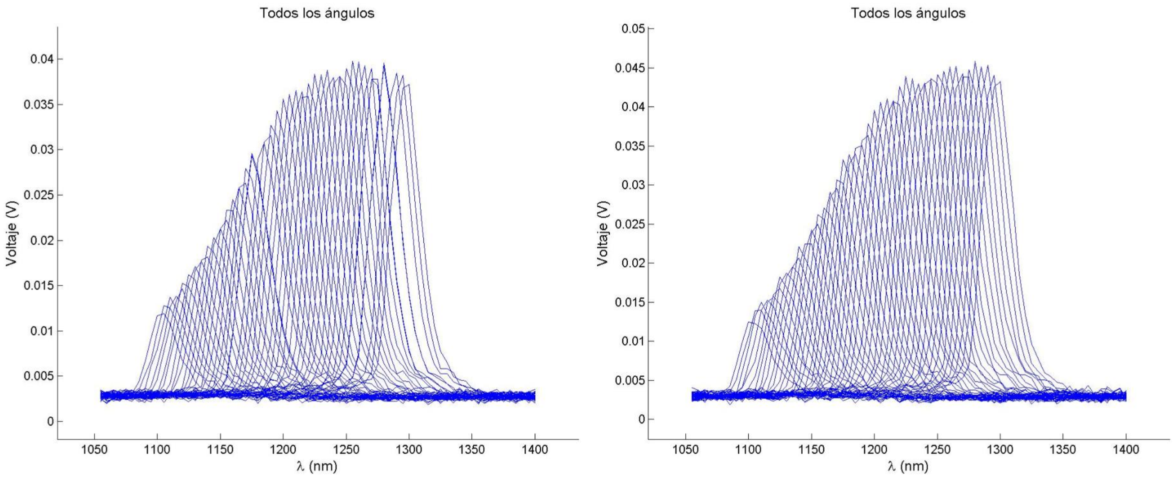

Fig. 4 VPHG J1b. As in figure 2.

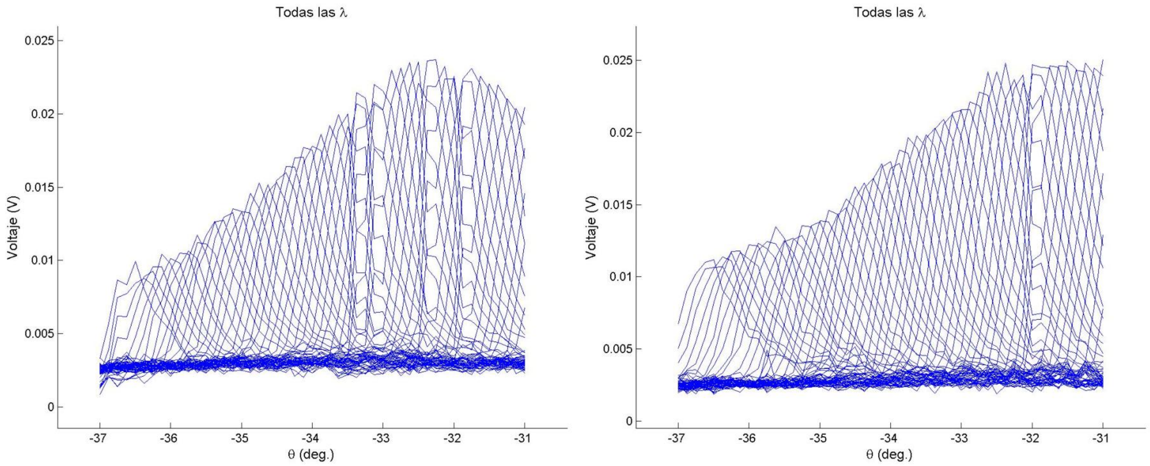

Fig. 5 VPHG H1a. As in figure 1.

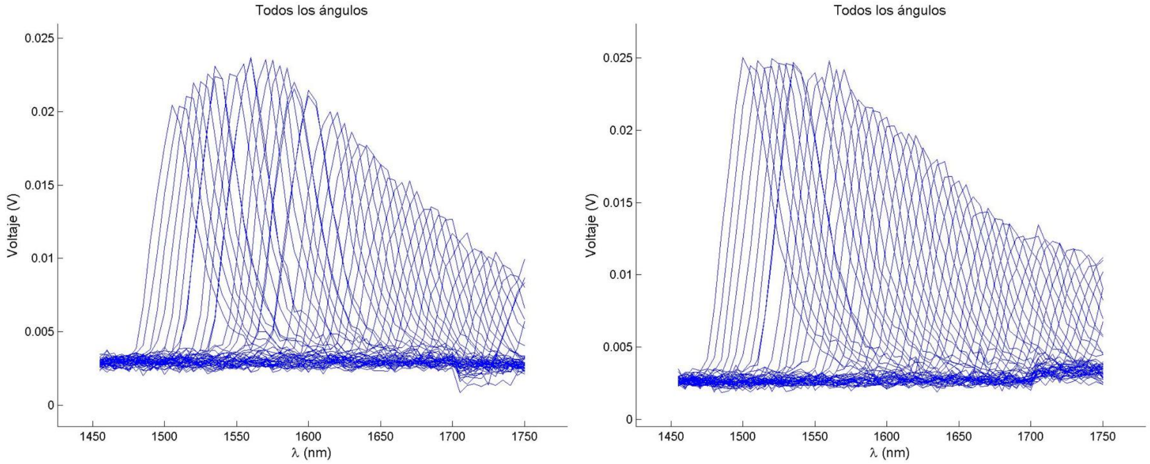

Fig. 6 VPHG H1a. As in figure 2.

Figures 1 to 10 show the recorded transmission, in voltage units, of the gratings being illuminated by a light beam coming from a monochromator, with spectral width of 8 nm which scans the selected wavelength range in steps of 5 nm. The detector is mounted outside the cryostat in a rotary table remotely controlled. Thus, the measurement proceeds by scanning in sequence through wavelengths and exit angles.

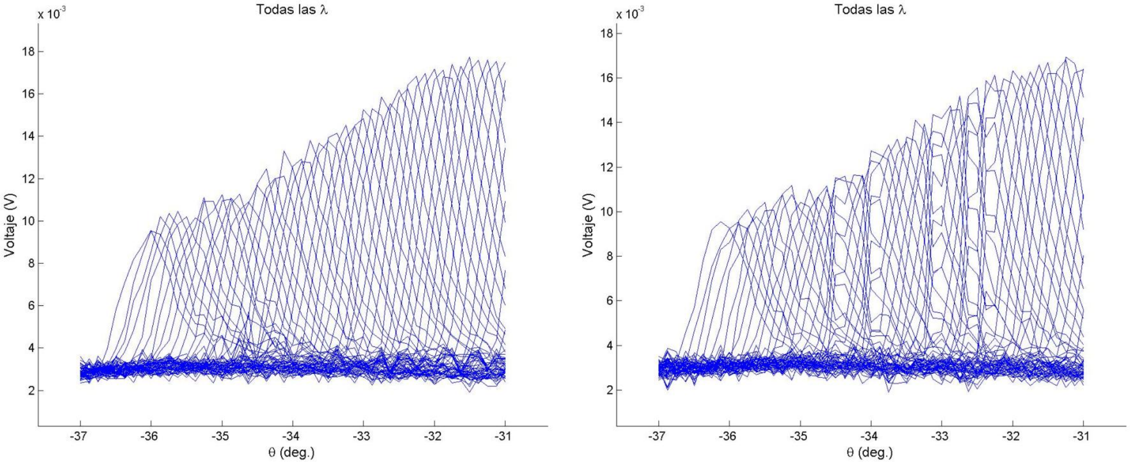

Fig. 7 VPHG H1b. As in figure 1.

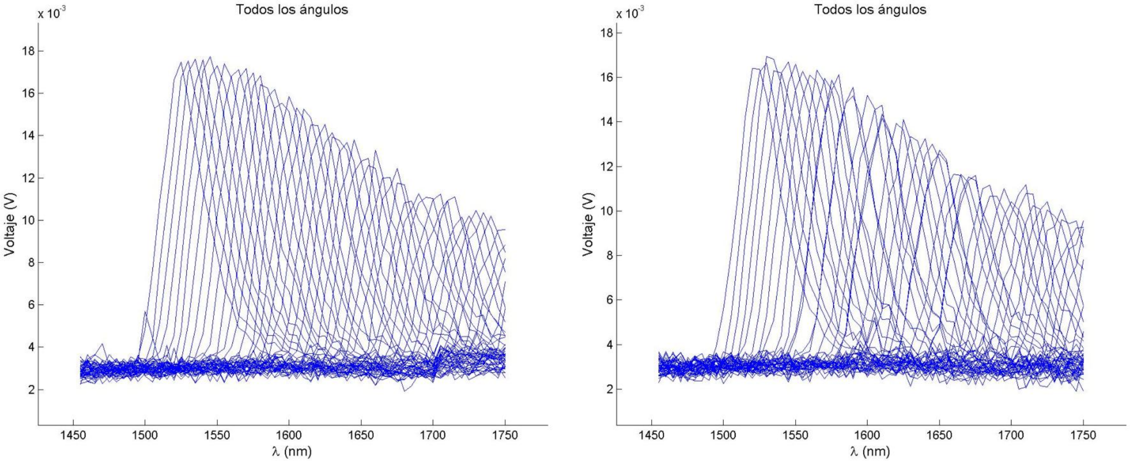

Fig. 8 VPHG H1b. As in figure 2.

2.1 Some conclusions from the measurements

The most important conclusion derived from these measurements is that temperature does not affect the operation of the VPHG as far as transmission is concerned or, if there are effects, they are below the sensitivity of the instruments used. The graphs obtained for ambient and cryogenic temperatures are practically identical to within the noise of the data. We therefore conclude that the materials used for the dichromatic gelatine were not significantly altered by cooling; above all, they were not frozen and maintained their properties with regard to the sinusoidal variation of the refractive index that gives rise to the behaviour of the element as a dispersion grating.

A slight displacement to the blue in the transmission curves, however, can be observed in the cold measurements with respect to those taken at ambient. This is to be expected due to the geometric contraction of the grating during cooling. On top of that, the small differences between the graphs of the two gratings for the same photometric band are surely due to errors or shifts that occurred in the mounting of the gratings.

Over time the *K* measurements are the noisiest, which is odd since, in this wavelength range, we are dominated, or heavily influenced, by ambient thermal emission and neither the external optics or the detector are cooled. However, it is permissible to conclude from figure 10 that the material of both the substrate, which was easily foreseeable since it consists of fused silica, and also that of the dichromatic gelatine continue to work in this range. Nevertheless, it is necessary to envisage a different mounting, a totally cryogenic one, in order to test science-quality gratings in the *K* band. Most probably, once the science prototypes are at our disposal, they will be mounted in a real NIR instrument to be properly tested. In particular, the reader is warned about the slightly different scales of the two panels, left and right ones, of the figures 9 and 10, which show the responses at RT and cryogenic temperatures. This is due to the presence of noisy spikes in the readings which perturb the uniformity of the measurements. These spikes overrun the scale of the plots, which we have selected to a similar value than in the RT case. We have preferred to present the data as they are, without filtering, to avoid introducing confusion. Anyhow, and in spite of these spikes, the overall shape of the graphs are nearly coincident.

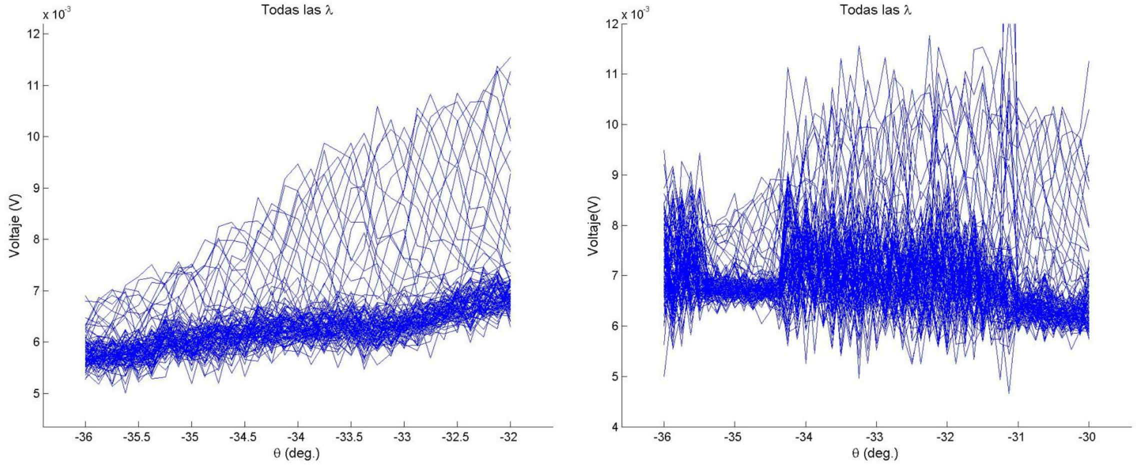

Fig. 9 VPHG K1a. As in figure 1.

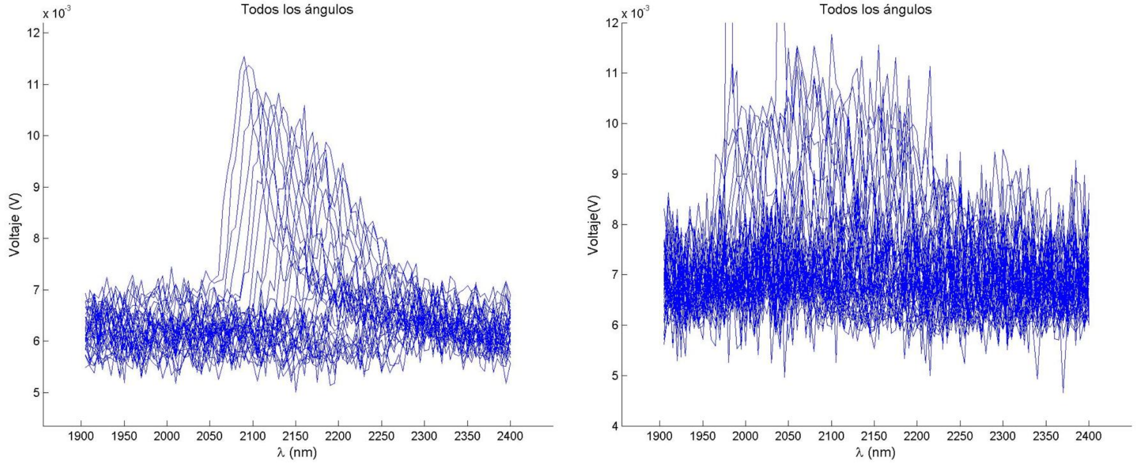

Fig. 10 VPHG K1a. As in figure 2.

3. MEASURING THE WAVEFRONT ERROR

In this part of the work, we aim to discover the effect of the VPH gratings on the light beam that traverses them: more specifically, the deformation produced in the wavefront at both ambient and cryogenic temperatures. In order to carry out these measurements, we have used the Zygo interferometer of the IAC's optical laboratory with the gratings mounted inside the cryostat, at both ambient and cryogenic temperatures.

With the set-up used there are elements, such as the cryostat windows, the mirror or the reflective surface, that can introduce deformations into the the wavefront. However, the only element whose behaviour varies from cold to warm is the grating, for which reason these deformations can be considered constant between measurements. Therefore, any observed variation in the wavefront due to change in temperature is due to the grating.

Since the grating is enclosed within the cryostat it has been necessary to work around various problems, which in some cases have introduced limitations in the tests. On the one hand, because of the location of the cryostat windows, it is not possible to centre the interference pattern of the beam from the interferometer which prevents taking measurements illuminating the centre of the grating. On the other hand, being limited by the windows, the measuring area (diameter of 28mm) is smaller than that occupied by the beam from the interferometer, which would have given rise to saturation problems if not limiting the exit beam. And finally, when carrying out the measurements in vacuo with the grating cooled by liquid nitrogen, we encountered a problem with the instability in the interference patterns, which made it difficult to take adequate and reliable patterns.

For the sake of brevity, we only show here two interferogrammes in figure 11 taken with the VPHG H1a at RT and 170K. As can be read from the caption, the differences in the recorded wavefront deformation between both temperatures regimes are negligible.

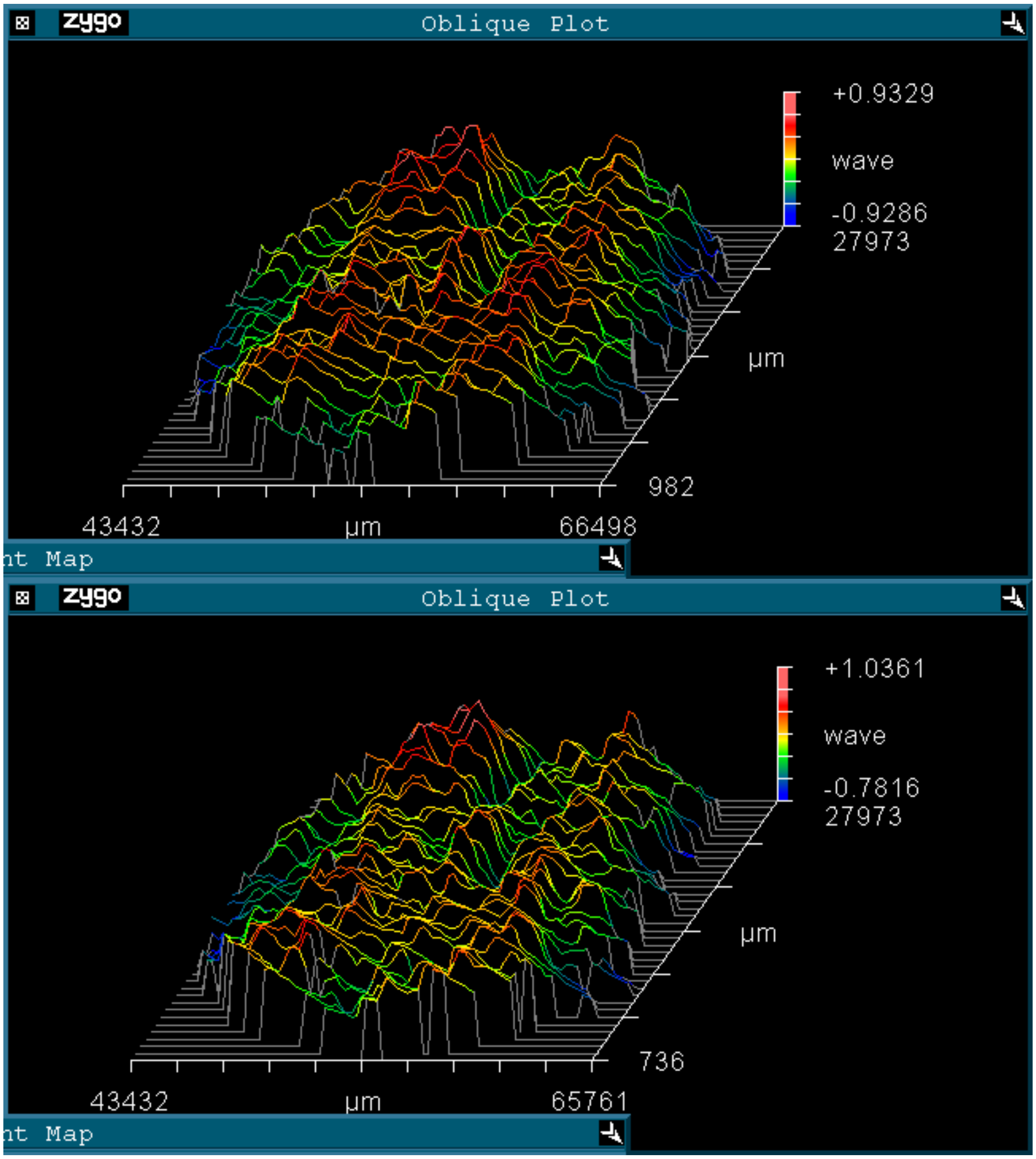

Fig. 11 VPHG H1a. Full grating interferogrammes. Top panel: T_{grat}: 293K; Deviation (wave): PV: 1.862; rms: 0.288. Bottom panel: T_{grat}: 170K; Deviation (wave): PV: 1.818; rms: 0.273.

The remaining VPHG prototypes exhibit similar behaviours, from which one can conclude that that temperature causes very little variation in the deformation of the wavefront.

With the data obtained, it is not possible to say whether the wavefront suffers more or less deformation as the temperature falls. The data are always of the same order. We therefore conclude, on the basis of these measurements, that the characterized prototypes function perfectly well at cryogenic temperatures, and that the materials of which they are constituted are suitable.

3.1 Others wavefront measurements

Within the run of the OPTICON JRA6 project, CSL performed a series of wavefront deformation measurements in a different VPHG prototype than the ones described in Table 1, but manufactured using the same methods and photosensitive material. In these tests[7] the wavefront diffracted by a typical VPHG were measured at various temperatures down to 150 K and at several thermal inhomogeneity amplitudes. Diffracted wavefront measurements show that the wavefront is extremely stable with temperature as long as this latter is homogeneous over the grating stack volume. Increasing the thermal inhomogeneity increases the wavefront error, which emphasizes the importance of the final instrument thermal design.

In the tests, the temperature was recorded by four thermocouples positioned at each corner of the grating and alternately on both sides to check the thermal homogeneity. It has to be noted that the grating has perfectly withstood various thermal cyclings down to the temperature of 133 K. Neither glass breaking, glue delamination nor shift of the blaze curve is to be reported. The initial cooling speed was about 10 K/minute. The maximal thermal difference we have induced between the blank sides was 30 K. These values are several times what is commonly encountered in the use if IR spectrometer instruments. So VPHGs can tolerate their working strains.

During the cool down, and after an initial deformation, the wavefront error remains stable as long as the temperature inhomogeneity does not increase. The wavefront error remains constant and its shape is comparable. Plotting the peak to valley wavefront error of our various measurements as function of the temperature but at constant temperature inhomogeneity gives a nearly horizontal straight line as it is shown by figure 12. On the other hand, when the thermal inhomogeneity increases, the wavefront error increases dramatically. This is shown in figure 13 for which several wavefront measurements were taken around 170 K before thermal gradients were relaxed. A difference of 20 K between the sides of the grating has increased the peak to valley wavefront error to higher than 3 λ. All these measurements allow the conclusion that the bending of the wavefront during the cooling is mainly due to the thermal inhomogeneity over the VPHG volume. Compared to that effect, the differential contraction of the various layers is negligible on the wavefront error. This is a very important observation since the thermal homogeneity of a grating can be controlled by a good instrument design.

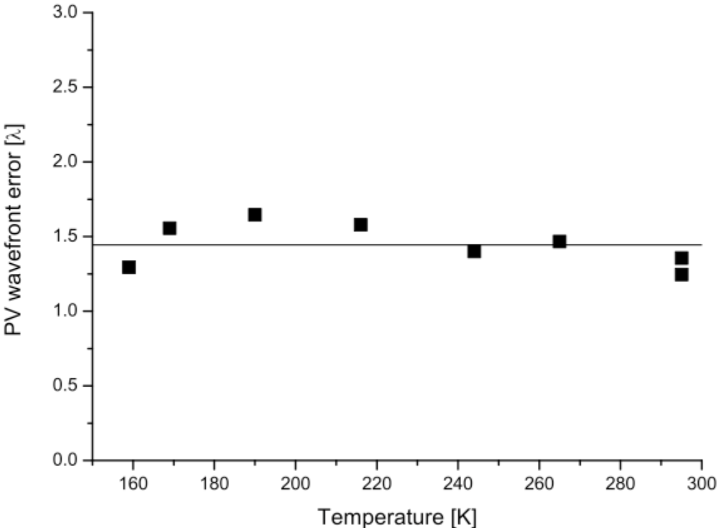

Fig. 12 Peak to valley wavefront error as function of the temperature at constant temperature inhomogeneity.

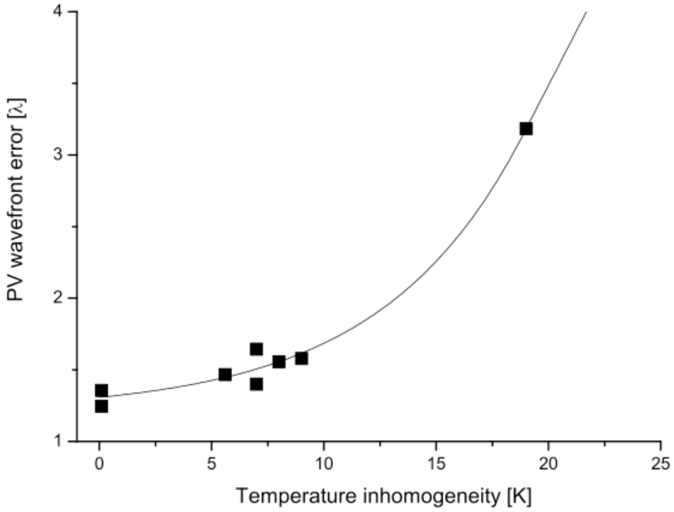

Fig. 13 Peak to valley wavefront error at low temperature as function of thermal inhomogeneity.

REFERENCES

[1] Arns, J.A., Colburn, W.S., and Barden, S.C, "Volume-Phase Holographic Gratings and the Efficiency of Three Simple Volume-Phase Holographic Gratings",Proc. SPIE 3779, 313–323 (1999).

[2] Barden, S.C., Arns, J.A., Colburn, W.S., "Volume-phase holographic gratings and their potential for astronomical applications", Proc. SPIE 3355, 277 (1998).

[3] Barden, S.C., Arns, J.A., Colburn, W.S., Williams, J.B., "Volume-Phase Holographic Gratings and the Efficiency of Three Simple Volume-Phase Holographic Gratings", PASP 112, 809 (2000).

[4] Barden, S.C., Williams, J.B., Arns, J.A. and Colburn, W.S., "Tunable Gratings: Imaging the Universe in 3-D with Volume-Phase Holographic Gratings (Review)", Proc. ASP Conference. 195, 552 (2000).

[5] Tedesco, J.M., Owen, H., Pallister, D.M.and Morris, M.D., "Principles and Spectroscopic Applications of Volume Holographic Optics", Analytical Chemistry 65, 441 (1993).

[6] Shankoff, T.A., "Phase holograms in dichromated gelatin", Applied Optics 7(10), 2101 (1968).

[7] Blanche, P.-A., Habraken, S., Lemaire, P., Jamar, C., "Diffracted wavefront measurement of a volume phase holographic grating at cryogenic temperature", Applied Optics 45(27), 6910 (2006).