techniques eliminating the influence of atmospheric turbulence on the fringe position. The system can also be used in differential interferometry mode in order to estimate the phase difference between two spectral channels. Handling dispersed data and three-beam combination will be among the new methods to be installed for the VLTI pipelines.

The data rate for the first VLTI instrument VINCI is less than 1 gigabyte per night. The data rates will be higher for AMBER (0.7 MB/s) and MIDI (2.3 MB/s). For MIDI this translates into more than 40 gigabytes of data per night. The handling of such data volumes brings the current system to its limits, in terms of overall throughput. For example, the DVD production is limited by the media capacity and writing speed. For this reason a new archive technology, based on magnetic disks rather than DVDs, is being evaluated and seems quite promising (Wicenec et al., 2001). The science VLTI instruments like MIDI will set very high requirements in terms of pipeline computation speed. Presently the VINCI pipeline can process data at about the same rate as they are acquired. MIDI will require two orders of magnitude in computation speed to perform this real-time data acquisition and processing. Solutions are being investigated using large VINCI data sets and MIDI simulated data.

Off-Line Processing and Analysis

For the scientific analysis of data, different interactive tools are provided on the off-line workstation, based on commercial data-analysis packages. The data can be browsed and organised by Observation Blocks with the Gasgano tool, which provides means of organising large amounts of data, classify them, view headers and call scripts on selected files. Gasgano can be used as a front-end graphical interface to the data reduction software.

Commands are provided to perform a second stage of calibration on the pipeline results. First the data are glued together and grouped by instrument modes. The calibration information can be tuned and the instrument transfer function is evaluated on the calibrator and interpolated with time. Finally it is possible to apply the calibration to science data and to model the intensity distribution of the source.

Conclusion

In the first phase of system commissioning, most of the calibration and analysis aims at characterising the performance of the interferometer, using two siderostats of 40 cm diameter separated by 16 m. For these tests, the pipeline provides photometry-corrected interferograms, uncalibrated visibilities, and the QC parameters which are instrumental to the assessment of the system performance. After this first stage of processing, data are transferred from the off-line work-station to the dedicated environments used for the performance analysis of each independent subsystem of the VLTI. The prototype tools for observation preparation can be tested for their usability in real conditions of observation.

In particular the interferometer transfer function, environmental parameters such as the atmospheric piston noise or the level of tunnel internal seeing, optomechanical performance and sensitivity of the delay lines are being analysed. A number of stars have been measured and a major criterion for stability could be verified: the equivalent point source contrast, i.e. the interferometer transfer function, was measured to be 0.87 with stability of about 1% over three days. This is far better than the required 5% over five hours. Other commissioning tests aim at verifying that fringes are found on any bright star in the specified field of view (60 degrees of zenith) or that low visibilities (down to 5%) can be measured.

After achieving the first fringes from the interferometer using the Unit Telescopes, the system is now used more intensively for the verification of the science performance of the system. More targets are observed and the pipeline is used to perform a preliminary calibration of the visibilities.

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Volume Phase Holographic Gratings Made in Europe

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This article is a shortened, combined and updated version of papers given at the August 2001 SPIE conference on Gratings in Astronomy (Monnet et al., 2001 and Habraken et al., 2001).

1. Grisms at ESO

The mission of the ESO Instrumentation Division is to provide our user community with state-of-the-art, operationally and optically efficient, versatile and stable instruments. Grisms have proven to be devices with which our mission can be carried out exceedingly well.

A grism is a surface-relief transmission grating that is applied to the hypotenuse face of a prism. The angle of the prism is chosen in such a way that the central wavelength of the first order spectrum is passed without deviation. Grisms with groove densities of up to 600 g/mm have an optical efficiency in the visible that is comparable to, or slightly better than, that of ruled gratings. Contrary to gratings, their zero deviation wavelength is nearly invariant with respect to slight orientation errors that may be caused by the insertion mechanism

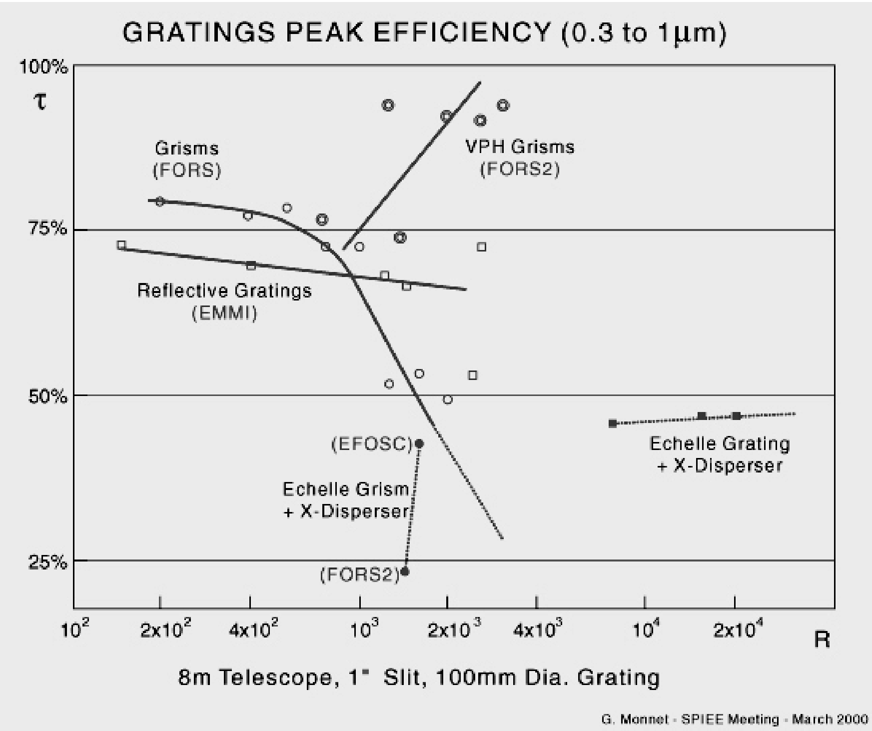


Figure 1: Peak efficiency τ of ESO gratings as a function of spectral resolution R for an 8-m telescope, 1″ slit and a 100 mm grating. The superior efficiency of VPHGs at R ~ 2000–3000 is evident.

or by flexure. Important technical advantages are also that the mechanics are simple, straight-forward and that grisms can be put quite close to the camera entrance which helps to reduce lens dimensions, vignetting and absorption.

ESO has been one of the first observatories to realise the advantages of grisms in combination with Focal Reducer systems and CCD detectors. In the EFOSC (ESO Faint Object Spectrograph and Camera) instrument that was developed for the 3.6-m telescope (Enard and Delabre 1983), focal reducer optics reimage the telescope focal plane to the CCD with the demagnification required to match the pixel size to the seeing disk. By inserting a grism in the parallel beam between the collimator and the camera, (and a corresponding slit in the telescope focal plane) the instrument is converted from an imager-photometer into a spectrograph. This allowed our users to image a field and study the distribution and morphology of faint objects, to do photometry and then to take low-resolution spectra of individual or multi-objects with the same instrument and in some cases even in the same night. In EMMI (ESO Multi-Mode Instrument, Dekker et al. 1986), an instrument for the ESO New Technology Telescope which is in many ways a precursor of the VLT, the same principles were applied. Instruments of the FOSC and MMI family that employ these optical and operational concepts are now in use at many observatories.

Of the 11 instruments, in various states of construction or operation, that were included in the set of first-generation VLT instruments, four Spectro-Imagers, FORS1 and 2, VIMOS and NIRMOS – covering the spectral range 360–1650 nm – are Focal Reducers using grisms. The total projected number of grisms in these instruments is about 50, with sizes matched to beam diameters between 90 and 160 mm.

The initial set of dispersers for these instruments was based on conventional grisms. For the modest spectral resolutions sought at the time (at most R ~ 1,000 for a one-arcsecond slit) they perform well with over 80% peak transmission and have relatively flat efficiency curves with wavelength. In the last years, however, the need for 2–3 times higher spectral resolutions became prominent. One reason is scientific, viz. the strong desire to study very high redshift galaxies, presumably of relatively modest masses since they belong to a prior epoch before small galaxies coalesced to form the giant ellipticals of today. The second one is more technical: roughly in the 630 to 1,650 nm spectral range, strong emission lines dominate the night sky background emission. Higher R ~ 2,000–3,000 permit to detect spectra of very faint objects between these lines, which would have been swamped at smaller resolutions. Attempts to fill that niche with classical grisms have been unsuccessful, with peak transmissions at 50% or lower, a large enough loss to make our instruments non-competitive compared to systems based on reflective gratings which can easily reach such resolutions with good efficiency. This had led ESO to investigate Volume Phase Holographic Gratings (VPHGs).

2. VPHGs – the Present

VPHGs imprint phase differences on the wavefront not by a surface relief, but by locally modulating the refractive index of a thin layer of a medium like Dichromated Gelatin (DCG). This material has for a long time been used for such diverse applications as head-up displays in military aircraft, optical beamsplitters, spectrally selective reflectors for solar concentrators and architectural applications (Stojanoff et al. 1997). Only recently has the

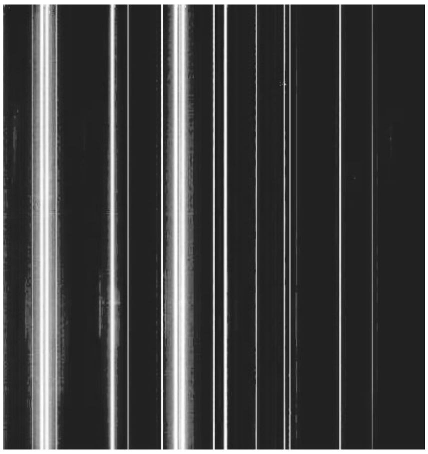


Figure 2: FORS2 He-Ne calibration spectrum with VPHG # 1028z (1028 l/mm blazed at 850 nm).

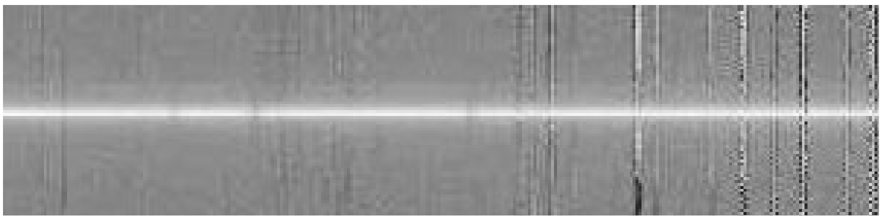


Figure 3: Spectrum of the dwarf galaxy FS27 (courtesy W. Zeilinger, Institut für Astronomie der Universität Wien). Same grism, 0.5 hr integration, resolution 78 km s^{-1}. The Ca II absorption triplet near 850 nm is clearly resolved.

technology been applied to produce dispersing elements for astronomy (Barden et al. 1998 and 2000). VPHGs are recorded holographically by interference of laser beams; subsequent processing in water and alcohol baths and baking results in a layer of the material with the desired index modulation. Because DCG is a hygroscopic organic material, the developed VPHG must be protected by a cemented cover plate.

VPHGs with an index modulation and layer thickness that is well tuned to the desired operating wavelength in first order can have peak efficiencies in excess of 90% at blaze. The blaze peak however is narrower than with surface relief gratings. This effect is less pronounced with larger index modulation and correspondingly thinner DCG. VPHG efficiency does not decrease with increasing line density as is the case with classical grisms; hence they are well suited to be used in existing straight-through focal reducer spectrographs to extend the range of spectral resolutions that can be accessed with good efficiency. (Fig. 1). Fortunately, VPHG/prism combinations also share the rotation invariance property of classical surface relief grisms.

Since 1999, five 92 mm × 92 mm VPHGs from Kaiser Optical Science Incorporated (KOSI) have been mounted and put in operation on the FORS2 at the VLT. Peak efficiencies are ~ 88% as shown in the FORS User Manual (Szeifert and Boenhardt, 2001) and together they cover the 500 to 1,000 nm range, with one arc second slit resolution between 1,000 and 2,700. Image quality is excellent (Fig. 2). Figure 3 shows an early result on a dwarf elliptical galaxy. User acceptance is excellent as shown by the healthy usage statistics since our first offering in October 2000 (Fig. 4).

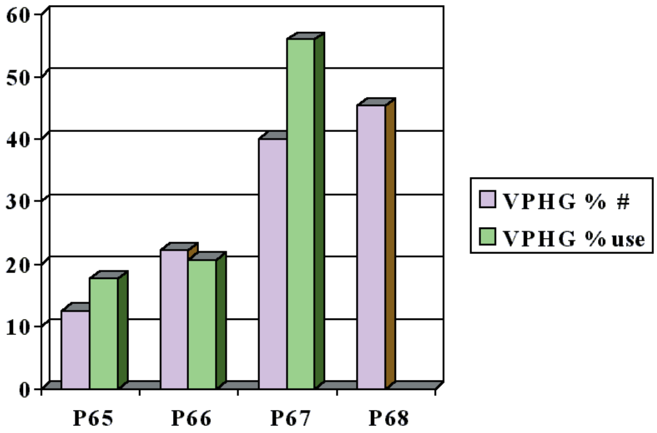


Figure 4: FORS2 VPHG usage statistics during semester allocations from P65 (start April 2000) to P67 (start April 2001 and up to 13 July 2001). Left bars: VPHG - % of all FORS2 grisms. Right bars: VPHG - % of total FORS2 spectrographic observations. From 1 October 1999 to 13 July 2001, total spectroscopic shutter open time at FORS2 was 283 hours.

3. VPHGs – ESO's Future Needs

ESO's current need is to get VPHGs substantially larger than the present 92 mm × 92 mm KOSI limit.

The VIMOS instrument, a 4-channel Visible spectro-imager, essentially to be used for massive redshift surveys of distant galaxies, has five different resolution/central wavelength settings and so it has twenty 150 mm × 150 mm grisms on-board. Twelve of these have bean earmarked for possible replacement by VPHGs.

Looking somewhat further ahead, we see the NIRMOS instrument, a near-infrared clone of VIMOS, which incorporates a –32 °C cooled optical box to increase efficiency in the H band, above 1550 nm. Higher resolution grisms are mandatory since in the whole wavelength range (1000 to 1650 nm) of the instrument the background is fully dominated by intense night-sky lines (Fig. 5). Cryogenic tests on various VPHGs (KOSI, RALCON, CSL) are being started by Golem-Merate.

On a still longer time scale, in the framework of upgrading the FORS1 instrument in the near-UV (320 to 400 nm), a high-line density, UV-efficient VPHG would be required for the study of tomographic maps of the Inter-Galactic Medium from R ~ 3,000 absorption-line spectroscopy of faint background quasars. The development of such a grating will be studied with CSL.

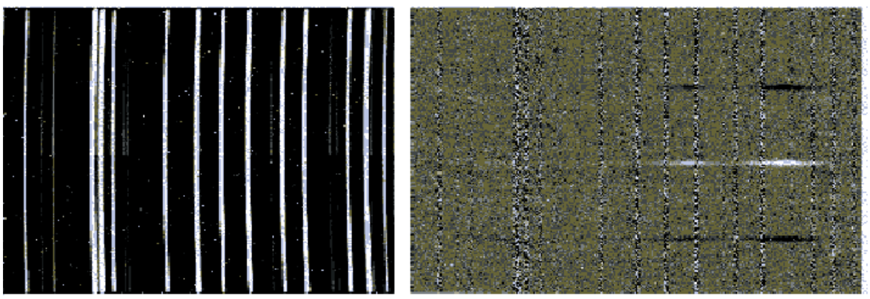
Finally, for the 2nd-generation VLT instruments, to be developed and deployed in the next 5–10 years, we may well base one or more instruments on the articulated or butterfly spectrograph concept (Bernstein et al. 2001). This approach would be especially useful for a long-slit (possibly fed by an integral field image slicer) spectrograph for the study of the dynamics and abundances of the gaseous and stellar components of external galaxies, with typically R ~ 7,000–10,000.

To satisfy these needs that exist at ESO as well as within the astronomical community at large, the EGUNA Consortium (ESO, Golem-Merate, University of Michigan, NOAO, AAO) has been set up. The short-term aim is to fund best-effort production of a batch of 10 large VPHGs – including 4 for ESO, 2 for Golem-Merate, 2 for the University of Michigan – at a new facility in the vicinity of the Centre Spatial de Liège (CSL) with significant financial help of the local Walloon government. This phase will end by mid-2002. The near-term goal is the creation of a commercially viable spin-off company.

4. The CSL and its Spin-off Activities

The *Centre Spatial de Liège* (CSL) is a group of 100 persons within the University of Liège. Its R&D activities are directed towards space instrumentation, optical metrology and testing (performance evaluation of the optical payloads). To create favourable conditions for the emergence of technological innovations and commercial activities, the Walloon public authorities have set up two resources, as shown in Figure 6.

Some of the CSL projects – mainly space research based – are emerging with high economic potential. A spin-off company incubator, WALLONIA SPACE LOGISTICS (WSL), was created close to the University by the Walloon Economy Ministry. WSL studies each project resulting from space research, and decides whether or



Upper left: R = 3000 ISAAC long-slit H-band spectrum of a z 2.44 galaxy, dominated by strong airglow OH lines. Upper right: spectrum after OH line subtraction. Lower right: trace of the galaxy spectrum.

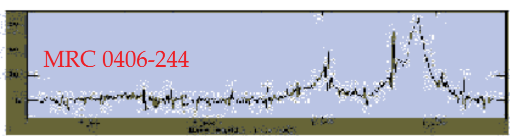


Figure 5: Demonstrating the need for higher resolution in the NIR

Figure 6: Diagram of resources available at the CSL research centre to spin-off companies

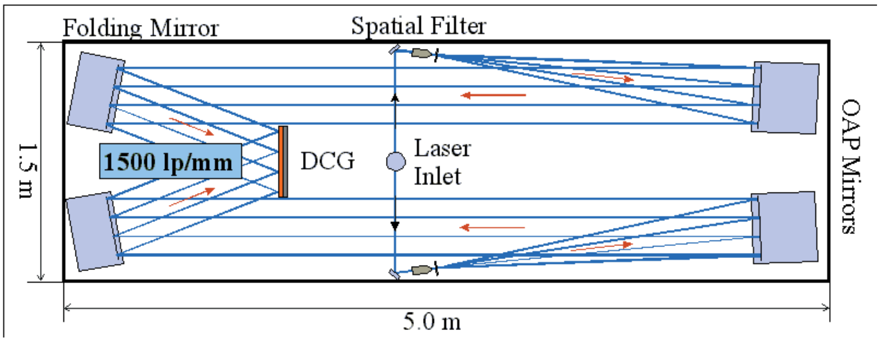


Figure 7: Simplified view of the holographic recording set-up. The laser is mounted below the optical bench.

not to support commercialisation, i.e. the creation of a spin-off company. During the incubator phase, the WSL supports and finances the basic needs of the baby spin-off (management, accounting, secretarial support and equipment).

5. CSL Background in Holography

CSL and the University of Liège have been involved in holography R&D programmes for 20 years. Interferometry, recording materials, and optical elements have been extensively studied. Dichromated Gelatin (DCG) is recognised world-wide as the holographic material with the highest diffraction efficiency thanks to its capability to record the highest refractive index modulation. The authors started to investigate that material in 1990 (Habraken et al. 1991) in the field of holographic optical elements. Very efficient reflection and transmission holographic gratings were recorded (Habraken et al. 1995 (1)).

Work was also conducted in the field of surface-relief gratings by recording on a photoresist material (Habraken et al. 1995 (2)). Polariser gratings (Habraken et al. 1995 (1–3)) and master gratings for embossed holography are realised in small size.

The theoretical background of CSL includes the implementation of the Rigorous Coupled-Wave Analysis (RCWA, Gaylord et al. 1983) code since 1994. This powerful tool is very flexible to model the performance of specific gratings.

This background experience of CSL was seen as a realistic starting point for a commercial activity in diffraction gratings. For that reason, the Walloon Research Ministry decided to fund this project. Our major threshold toward the market of Volume Phase Holographic Gratings (VPHG) was certainly the size and the quality criterion that is required.

6. New VPHG Facility: Funding and Construction

Following initial discussions with the five members of the EGUNA consortium, CSL decided to investigate the production of (at least) 30 cm diameter VPH gratings. Total funding amounts to 642 kEuro of which 81% is contributed by the Walloon Government and 19% by the consortium. The definition and procurement activities started in November 2000.

A new DCG coating facility has been subcontracted, built and delivered that can apply DCG layers with thickness values ranging from 5 to 25 μm with high uniformity (local deviation lower than 1 μm PV) over the 40 × 40 cm area.

The holographic recording of plane gratings requires a set-up with two interfering collimated laser beams. Recording is performed on a 1.5 m × 5 m optical bench, using an argon laser delivering 4.8 watts (single line at 488 nm TEM 00). The set-up geometry is shown in Figure 7. Two off-axis parabolic mirrors (38 cm diameter) collimate the beams. To adjust the illumination angle, two flat mirrors fold the beams. Thus, the fringe frequency can be changed continuously from 300 l/mm up to 3000 l/mm. Higher frequency could be recorded with a minor change in the optical set-up.

Laboratory facilities for gelatin development have been set up with large regulated baths and a forced convection oven to dry the final grating before encapsulation.

These three laboratories, i.e. coating, exposure, and development, together cover 100 m^2. They are equipped with air conditioning which regulates temperature, hygrometry and cleanliness up to class 10,000. Laminar flow benches provide local filtering up to class 100 in sensitive areas, utilising the technical know-how of CSL in space optical payload qualification. The hardware deliveries were almost completed by October 2001.

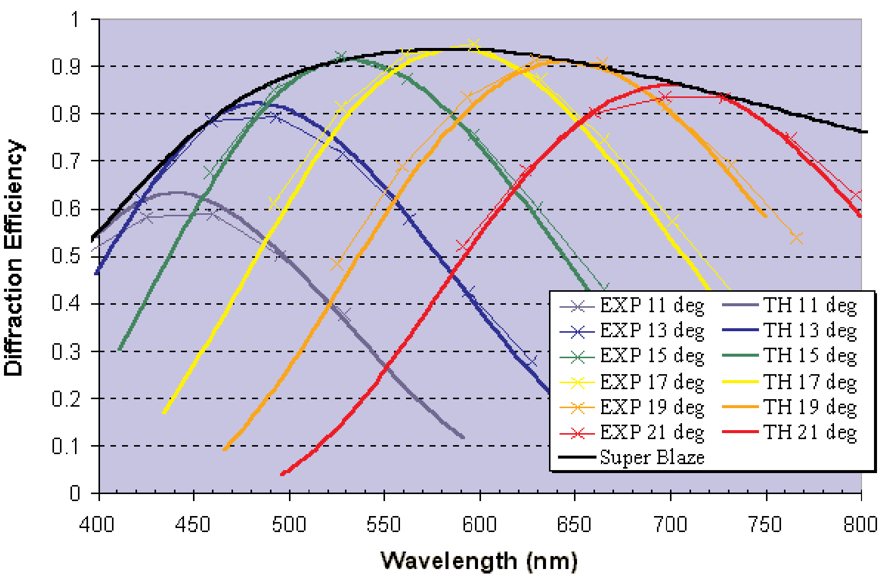


Figure 8: First-order unpolarised intrinsic diffraction efficiency of a 1000 l/mm VPHG sample manufactured at CSL. By tilting a VPHG, the efficiency at a given wavelength can be optimised; the resulting envelope is called the Super Blaze.
Measurements were made at Golem-Brera, assuming 8% surface losses. Actual losses are higher by 3–5%, so peak efficiency will approach 98 %. Theoretical fits based on RCWA assuming grating thickness = 9 μm and Δn = 0.0325.

7. Sample Grating Performance

The initial survey among the members of the Consortium indicated that the CSL should address a wavelength range of 400–1500 nm and a line frequency of 300–3000 l/mm or even more. High efficiency over a wide spectral range is required. With volume phase gratings, this requires a thin layer with the highest possible refractive index modulation.

In parallel to hardware definition and procurement, tests have been performed on small samples to tune the process of recording and development of DCG. Preliminary results are presented below that show potential for further improvement.

DCG offers numerous degrees of freedom. The major parameters are related to the chemical composition, the exposure energy, and the development process. The gelatin thickness must be adapted to the useful wavelength. The easiest theoretical understanding is given by the following relation (Kogelnik 1969):

$$\eta = \mathrm{Sin}^2 \frac{\pi \Delta n d}{\lambda \mathrm{Cos}\theta}$$

where

η is the diffraction efficiency (1st-order TE-polarisation),
λ is the central wavelength in air,
θ is the internal angle of incidence,
Δn is the index modulation,
d is the grating thickness.

From visible to IR wavelengths, the product $\Delta n.d$ must be as high as possible to maximise the diffraction efficiency over a wide wavelength range. When the process optimisation reaches its limits, the only way to increase $\Delta n.d$ is to increase the grating thickness. For that reason, our optimisation phase addressed a variety of thickness. Until now, CSL has reached promising values:

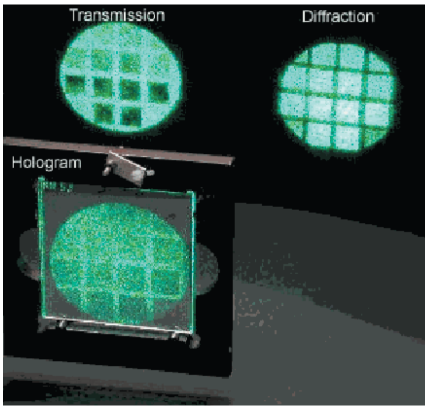


Figure 9: Picture showing the vanishing of the zero-order in VPH grating samples at 514.5 nm.

	Index modulation Δn	
Film Thickness	Measured	Target (2002)
15 μm 10 μm 7 μm	0.030 0.035 0.040	>0.035 >0.040 >0.045

With the above set of parameters, the range of possible blaze wavelengths is 570 nm (and below) to 950 nm. Production of VPHG blazed up to 1500 nm is possible, but would have to be validated on thicker layers.

Accurate spectral measurements have been performed by Golem at Brera Observatory. Figure 8 presents the performance of a 1000 l/mm grating. The physical gelatin thickness is 10.5 μm but the theoretical fitting of the super blaze is consistent with a grating thickness after development of 9 μm and an index modulation of 0.0325[1].

These results demonstrate the progress made by CSL to convince the scientific community, represented by the EGUNA consortium, of our capabilities. Very high diffraction efficiency has been reached even in the near IR.

Figure 9 is a picture of several small gratings diffracting the Ar laser beam (514.5 nm). The high efficiency is evident when the zero-order transmitted beam is vanishing: all the incident energy is transferred to the 1st-order diffracted beam.

8. Next Phases and Schedule

Following these encouraging results, CSL will continue to enhance the DCG process with regard to the index modulation, the diffraction efficiency uniformity and the scatter level on small samples.

The progress should allow us to start the recording of large VPH gratings for the EGUNA Consortium in January 2002. CSL is committed to produce and deliver 10 gratings to the EGUNA consortium by the end of June 2002.

The success of the project and the interest from the astronomical community will be the basis for a decision to set up a spin-off company with the help of WSL in 2002, directly after the delivery of the 10 gratings. The main product of that spin-off will be large-scale VPH gratings but further applications are expected (holographic optical elements, ion-etched surface-relief gratings, etc.) CSL will keep a very close contact with the spin-off company to ensure success; hardware and human resources shall be shared, at least during the first years.

[1]Fitting based on individual spectral measurements indicates a grating thickness of 8.5 μm with Δn = 0.0345.

Inquiries for future new deliveries should be directed to shabraken@ulg.ac.be

9. Conclusions and Summary

For upgrading of existing ESO instruments, as well as for 2nd-generation VLT instruments, VPH gratings offer significant advantages over conventional grisms and reflection gratings in terms of efficiency and spectral resolution.

The infrastructure necessary to achieve a high quality level in large VPHG manufacturing has been implemented at CSL; process tuning and optimisation shows promising results.

With the demonstration of good performance in VPH grating sizes up to 30 cm diameter, CSL expects to quickly generate a commercial interest.

After the present R&D phase that will end mid-2002, the technological knowledge will be transferred to a new commercial company with core business in the field of holographic optical elements, including gratings.

10. Acknowledgements

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