Cascaded holographic spectrographs for astronomical applications

advanced modelling and experimental proof

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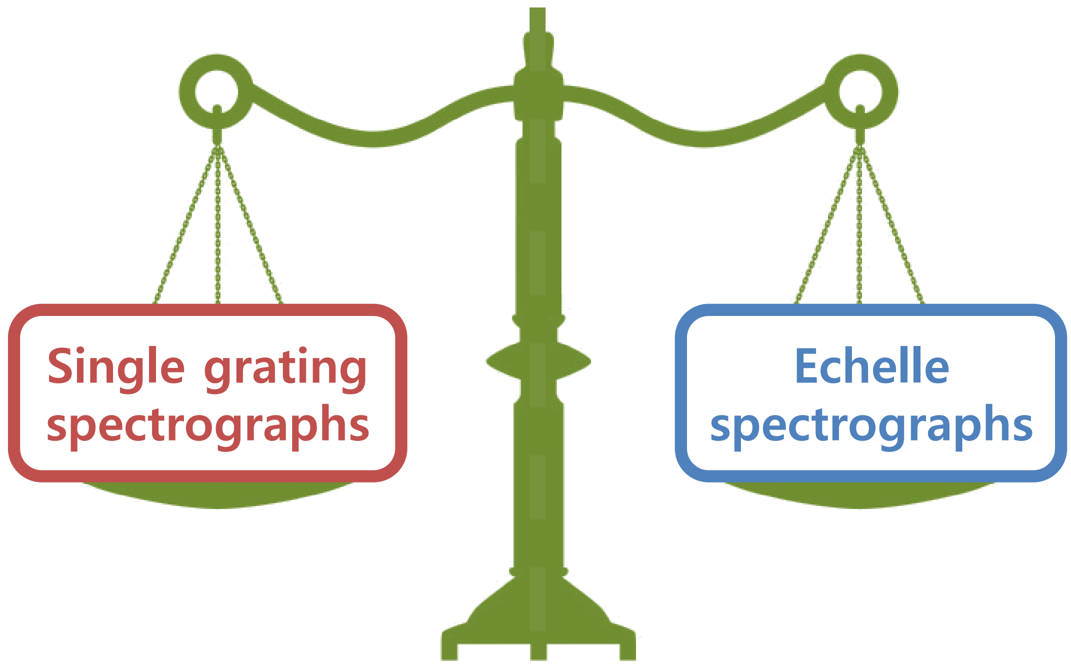
Outline of the talk

1. Spectrographs types and the performance trade-off
2. Design concept of the cascaded holographic spectrograph
3. Early wedge-based design
4. Design and modelling of the spectrograph lab prototype
5. Experimental proof of thee concept
6. Generation 2 – multiplexed spectrograph

Spectrographs types



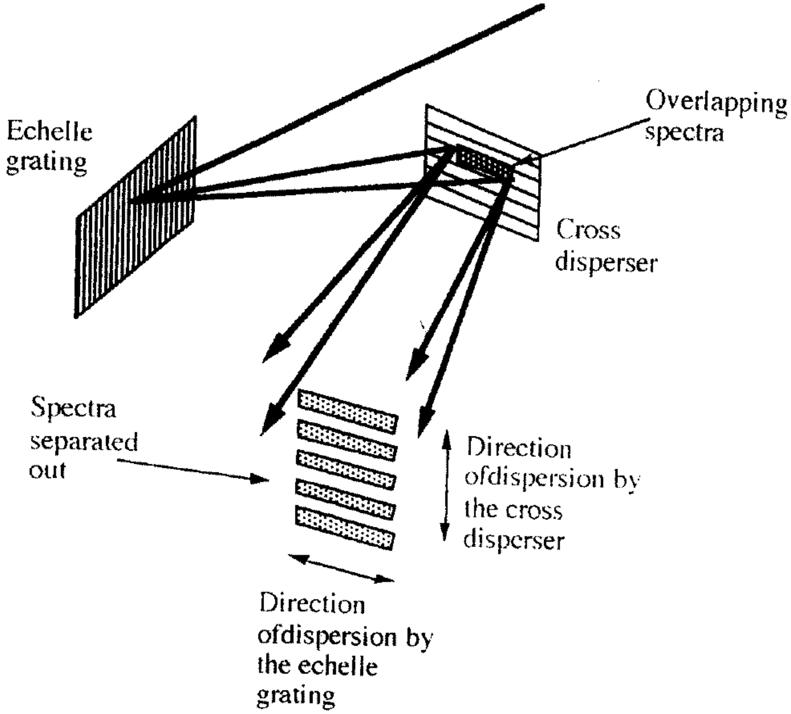
+High throughput
+Simple optics
-Low spectral resolution
And/or
-Narrow working range

+High spectral resolution
+Wide spectral coverage
-Limited throughput
-Complex optics +
cross-disperser

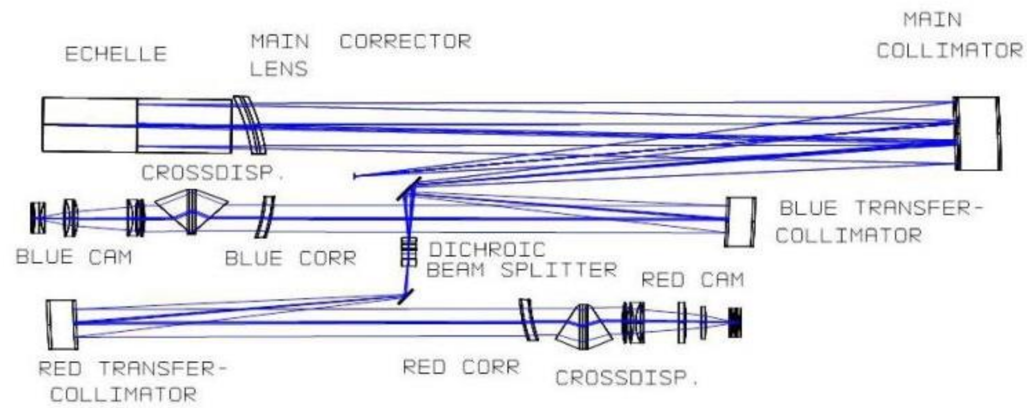
Echelle spectrographs

- ✓ Light is dispersed to multiple diffraction orders
- ✓ The orders are separated by a cross-dispersing prism or grating
- ✓ High resolution 2D spectrogram is focused onto detector

The principle



PEPSI spectrograph @LBT

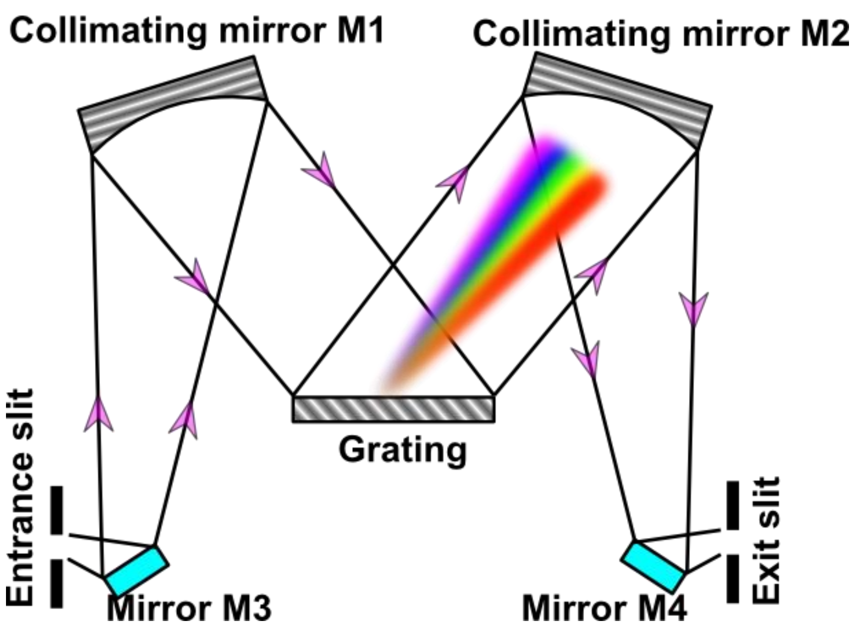


Wavelength coverage……..383 to 912 nm
Spectral resolution…………40.000/120.000 /270.000
Throughput ………………… 15 % (@650 nm)
to 10% (@900 nm).

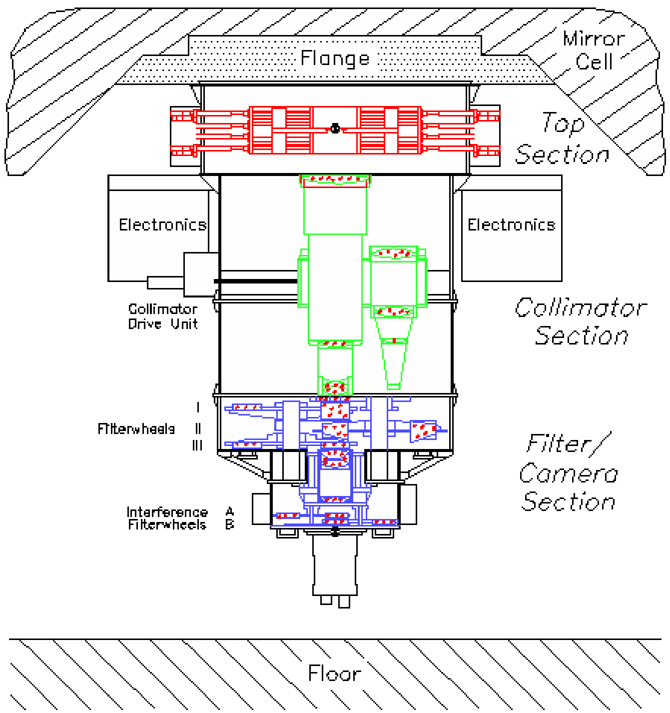
Single grating spectrographs

- ✓ A single grating working in one (typically +1st) diffraction order is used
- ✓ Grism(=grating+prism combination) is used to keep an axial arrangement
- ✓ A few exchangeable gratings can be used to cover an extended range

The principle

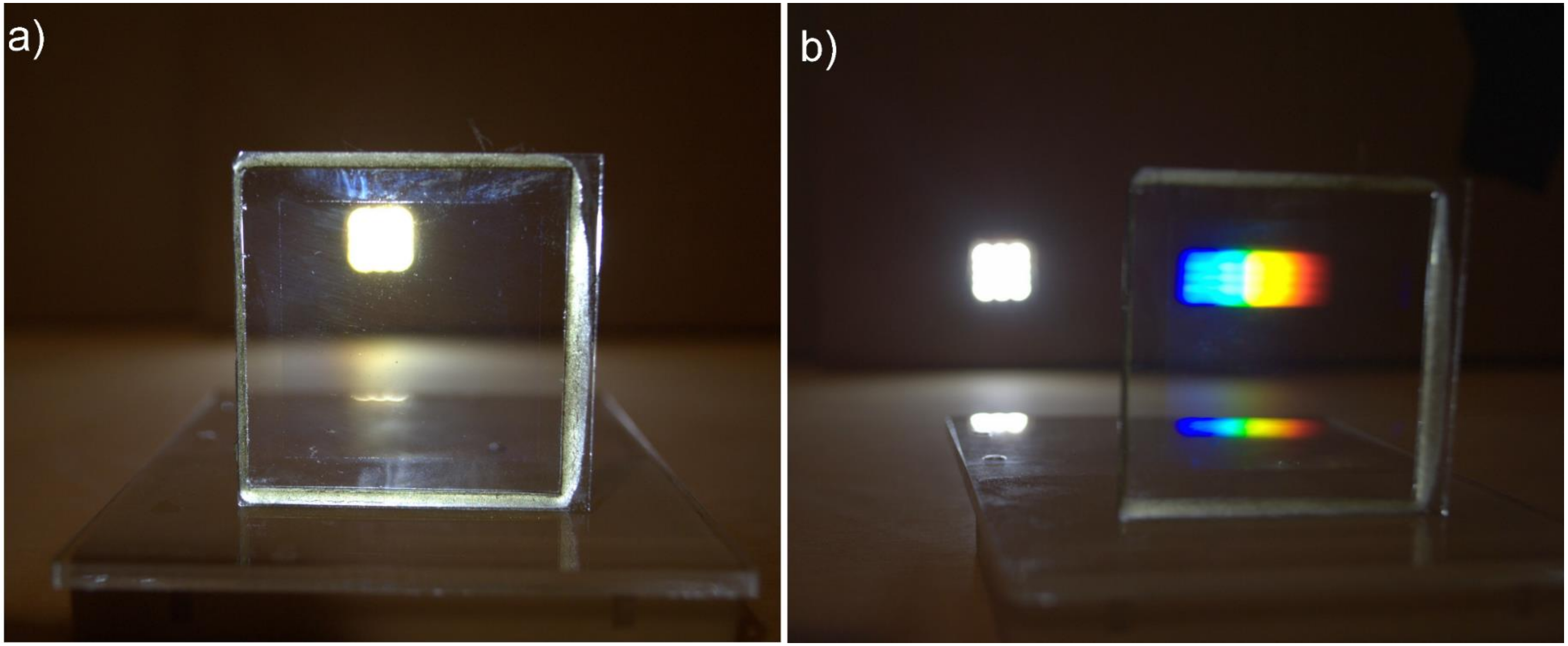


FORS spectrograph @ VLT



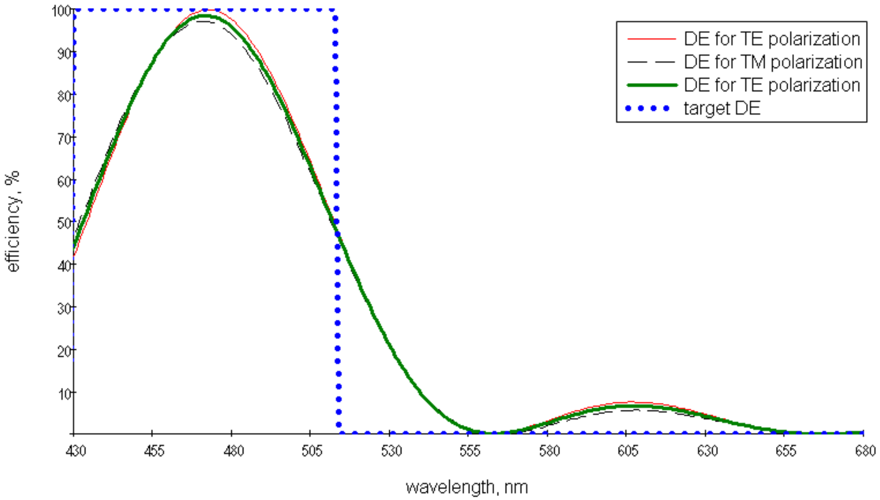
Wavelength coverage (G2)……..525 to 740 nm
Spectral resolution……………….1230
Throughput ……………….. ……..Up to 82%

Volume-phase hologrbackground

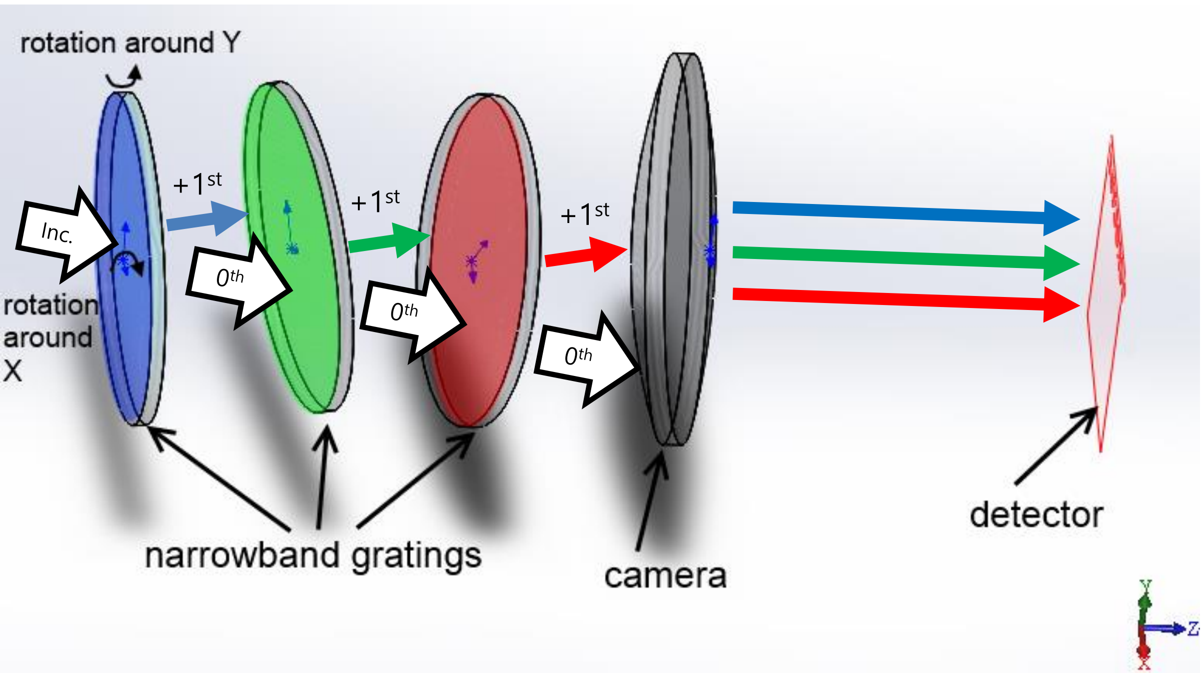


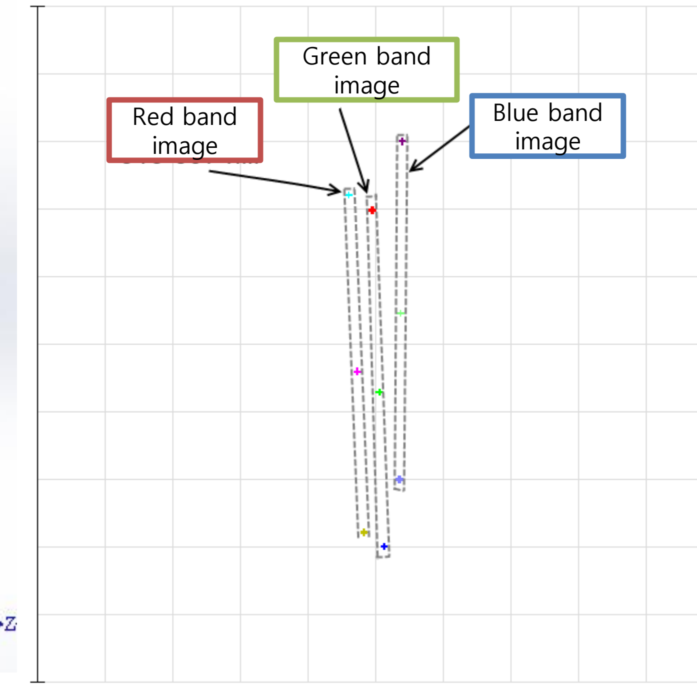
Top – photo of a LED taken through a typical volume phase holographic grating in the 0th (a) and +1st (b).

Bottom – typical diffraction efficiency curve of a VPH grating



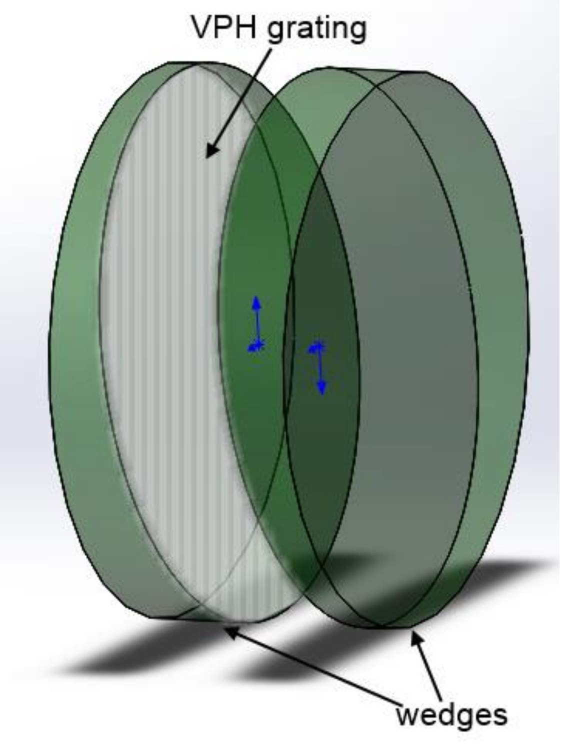
Cascaded spectrograph concept

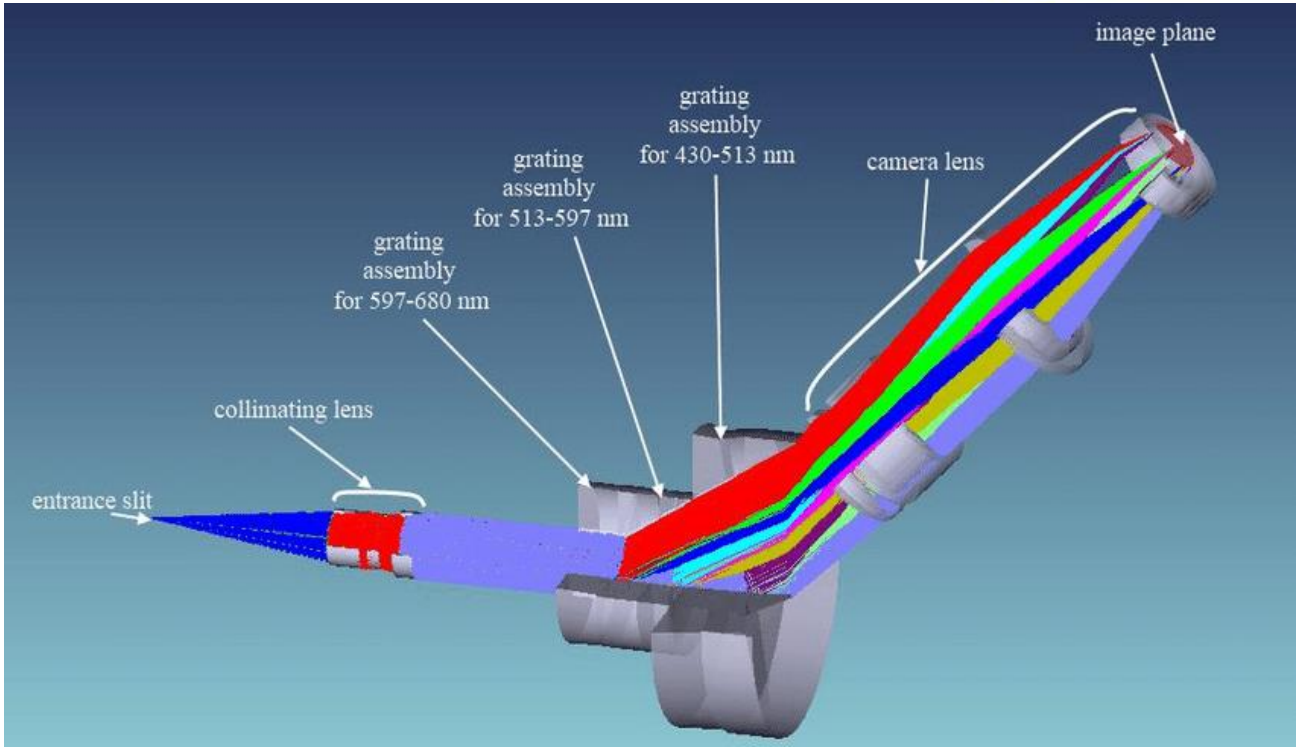




Left – cascaded holographic spectrograph principle
Right – spectrogram format

1st stage design

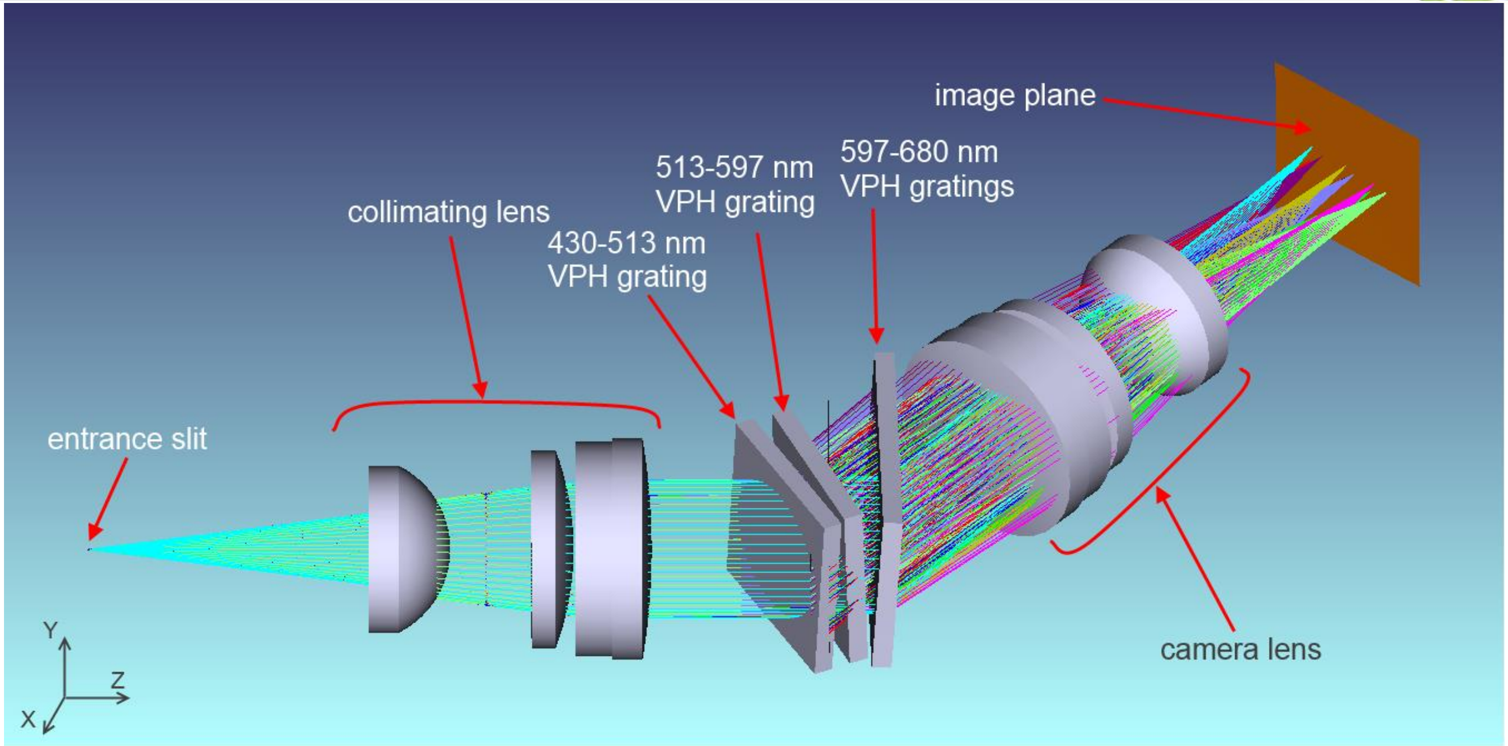




The first wedge-based optical scheme

Wavelength coverage	430-680 nm
Target spectral resolution	~5200-7900
Entrance slit	0.03x1 mm
Collimator&camera	Customized triplet-based lenses 170 mm, F/3.8

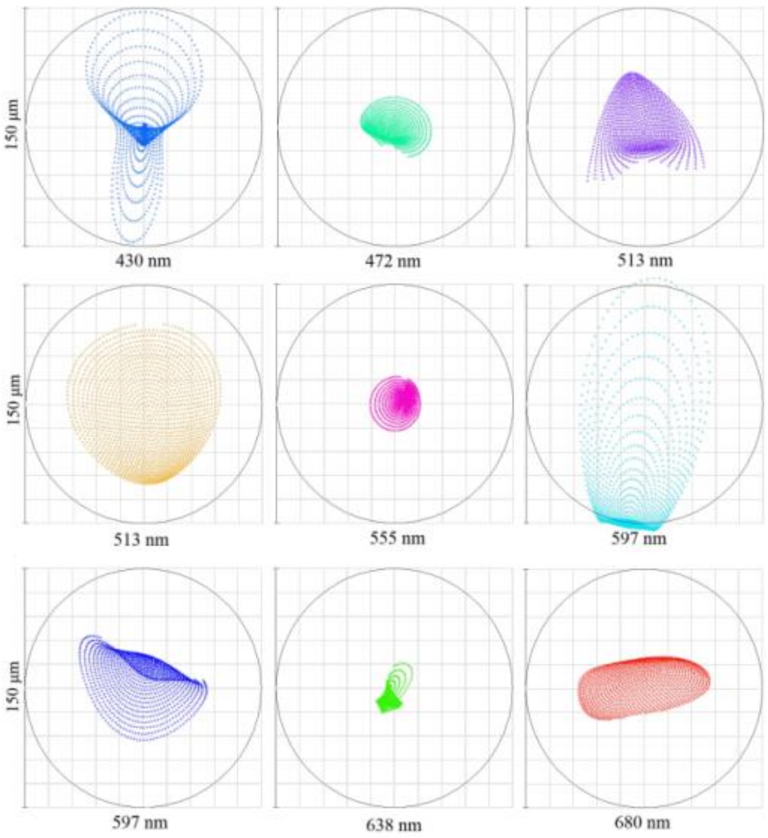
Lab prototype optical design

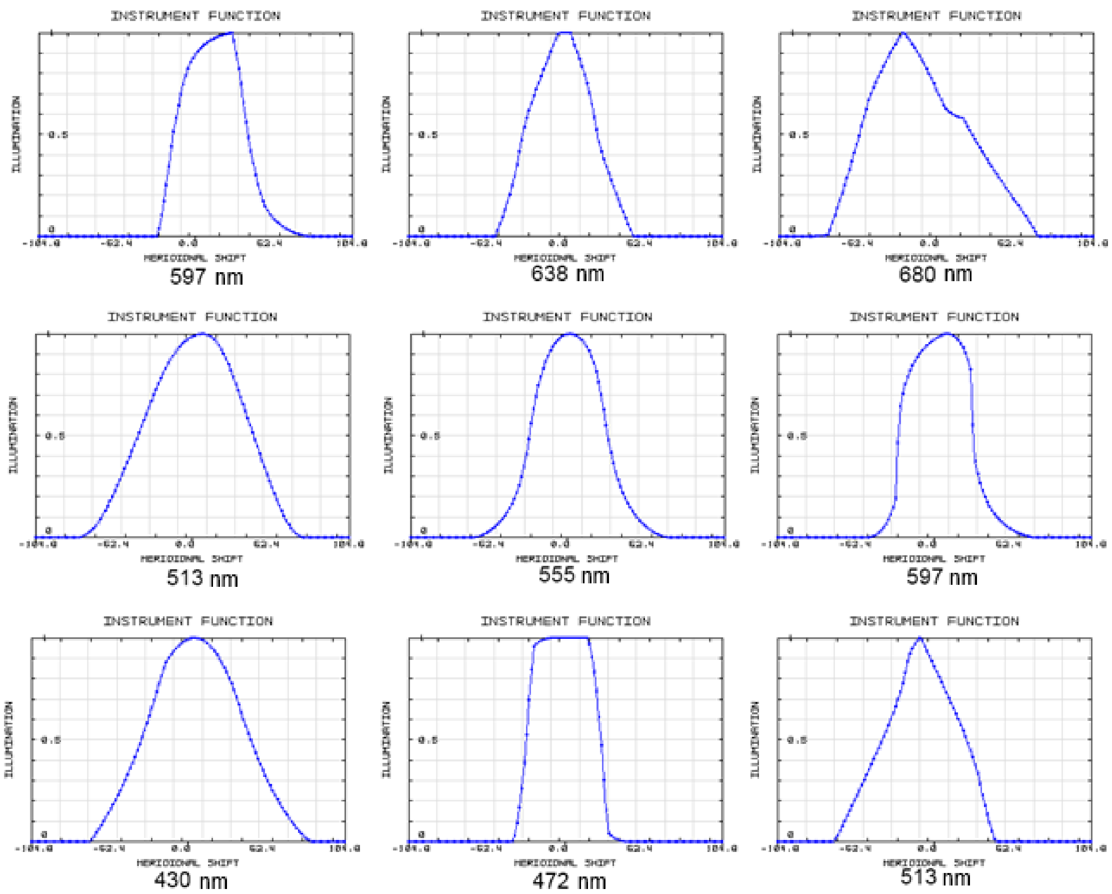


General view of the cascaded spectrograph optical scheme

Wavelength coverage	430-680 nm
Target spectral resolution	~1500-5000
Entrance slit	0.03x1 mm
Collimator&camera	Two identical commercial Tessar-type lenses 135 mm, F/4

Image quality

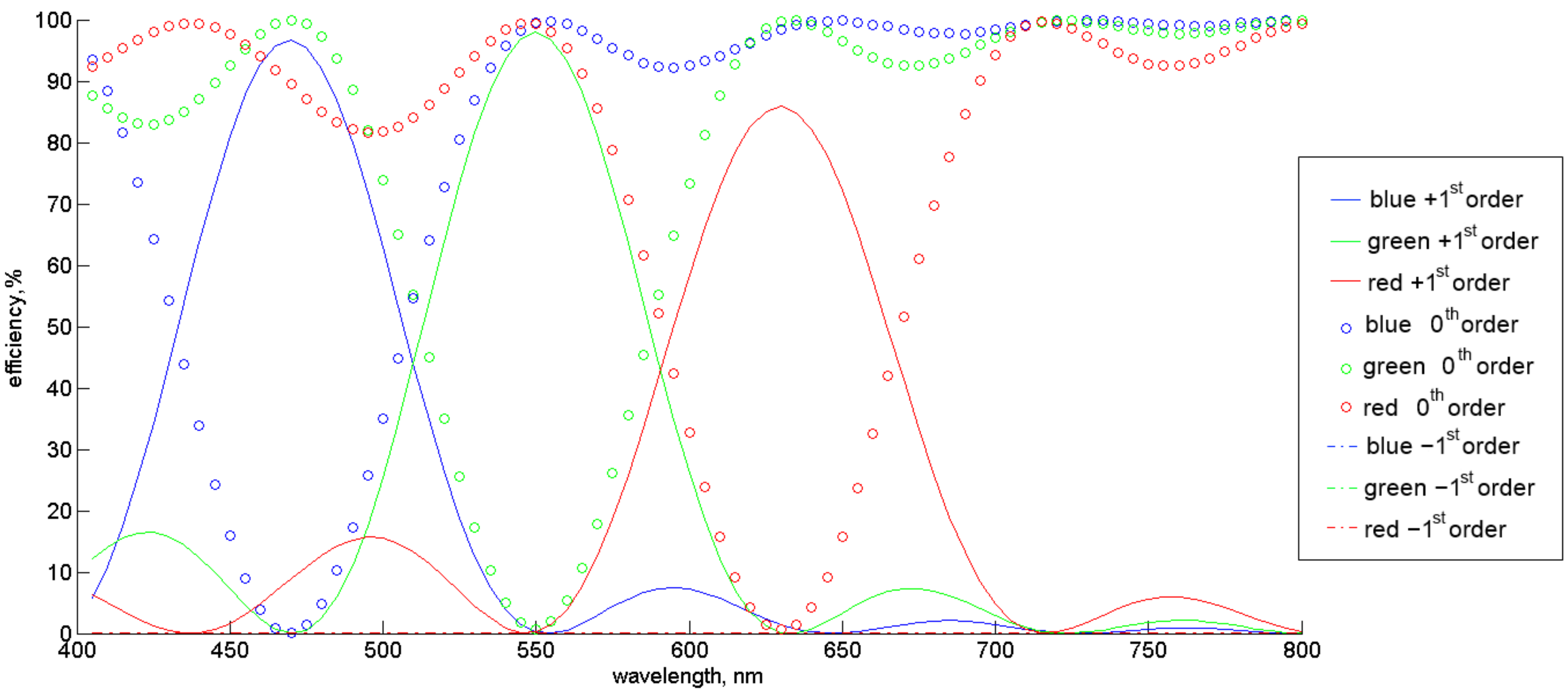




Left – spot diagrams of the spectrograph (circle diameter is 150 um)

Right – instrument functions for 30 um slit

Lab prototype gratings design



Gratings diffraction efficiency

Waveband (nm)	430-513	513-597	597-680
Grooves frequency (mm^{-1})	1726	1523	1205
Holographic layer thickness (μm)	10	12.8	19.1
Refraction index modulation	0.023	0.021	0.014
Fringes inclination angle	3.305°	6.143°	12.602°
First recording angle	33.025°	34.485°	40.776°
Second recording angle	-21.914°	-14.125°	0.690°

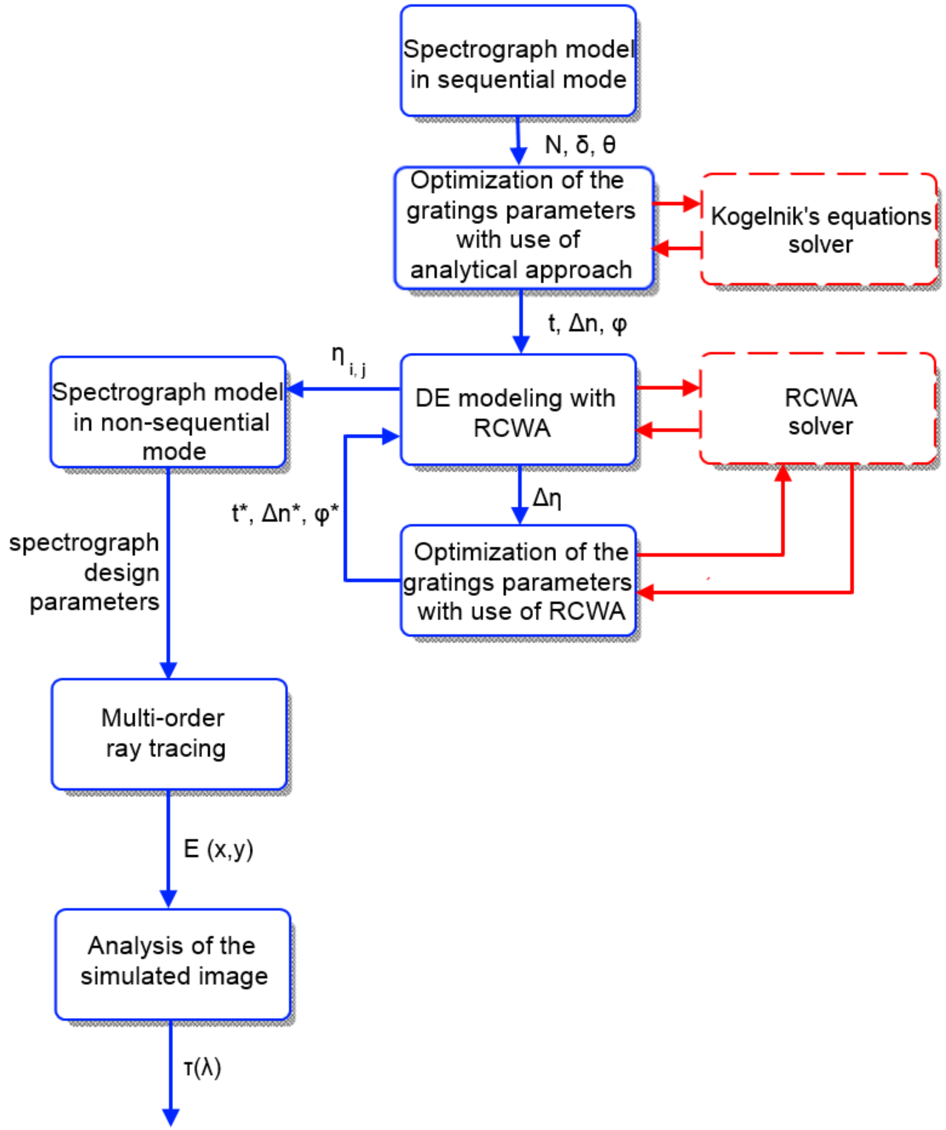
Lab prototype modelling (I)

Rigorous Coupled Wave Analysis
(*reticolo* software)

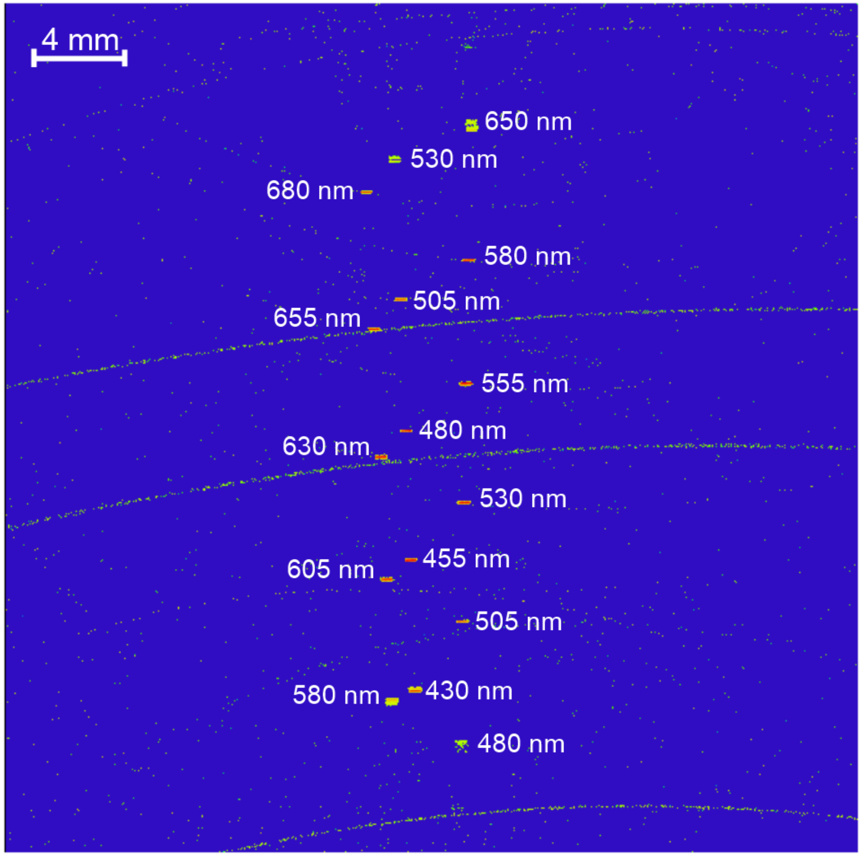
+

Non-sequential ray tracing
(*Zemax*)

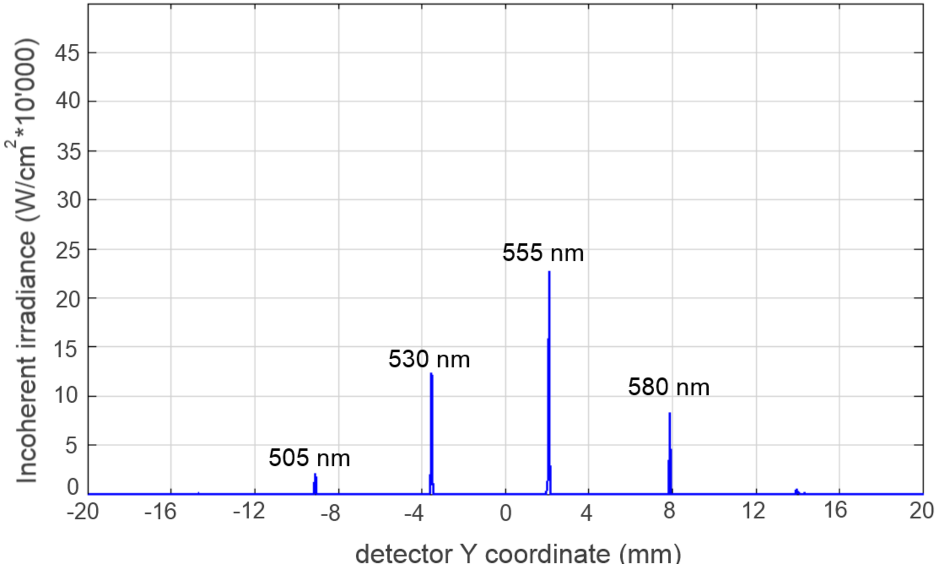
Design and modelling algorithm



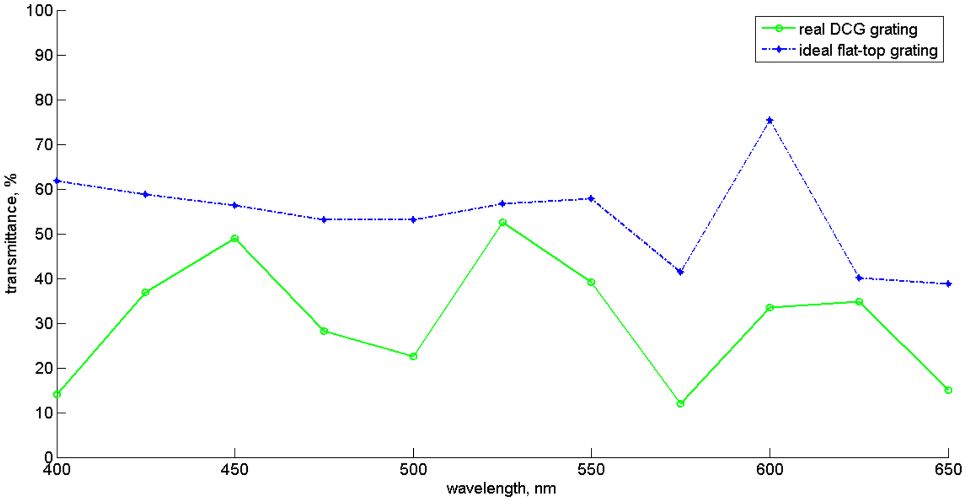
Lab prototype modelling (II)



Full-frame simulated image in log scale

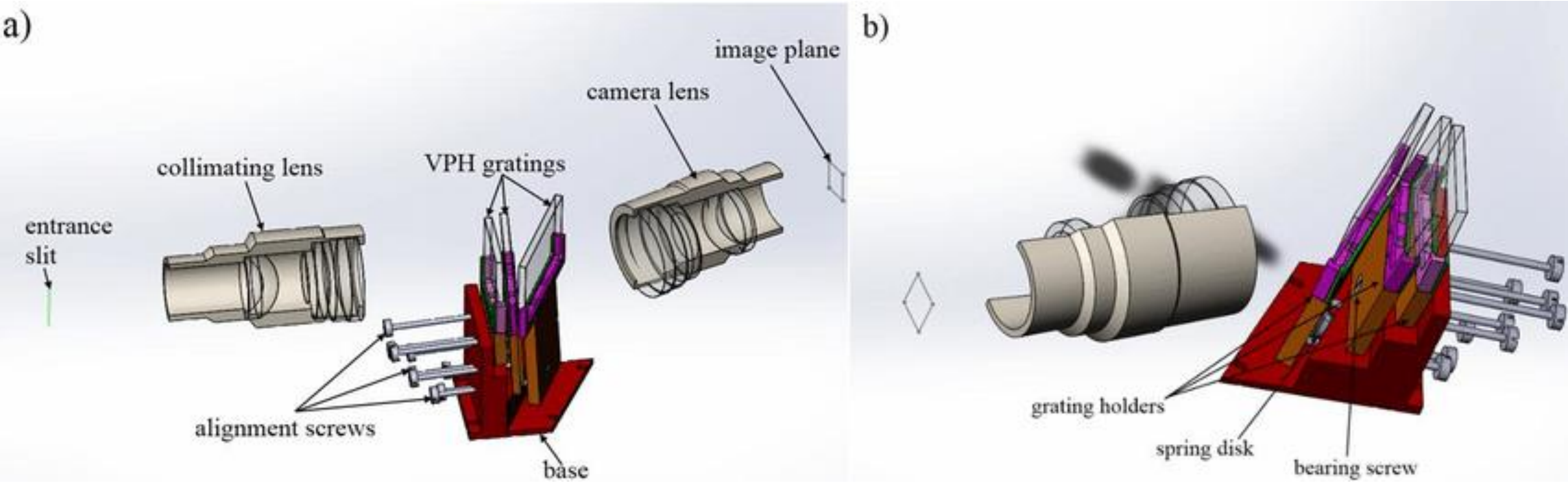


Irradiance across 513–597 spectral line



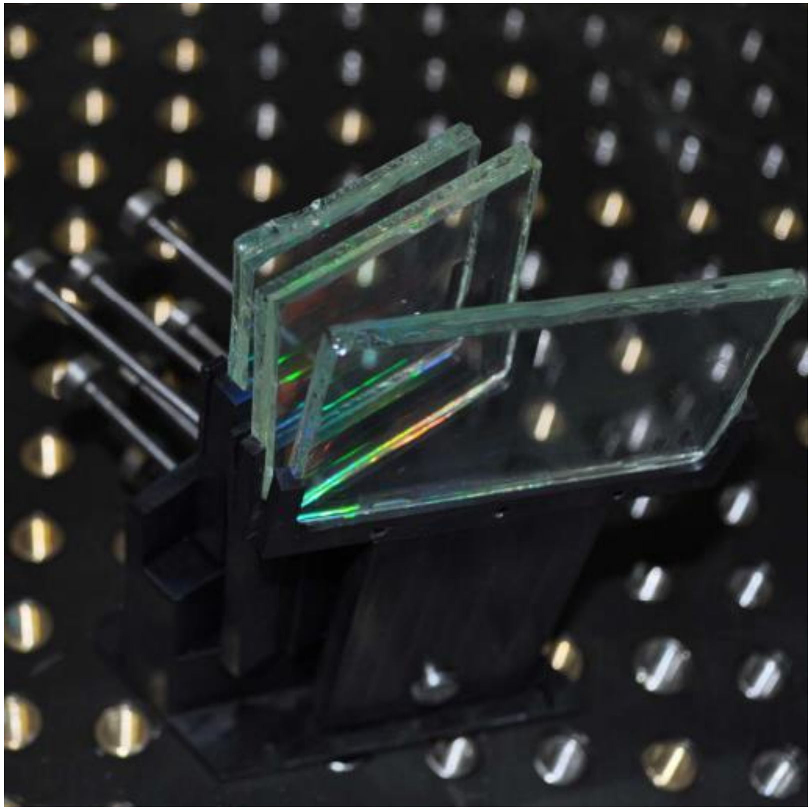
Total spectrograph throughput spectral dependence

Lab prototype mechanical design

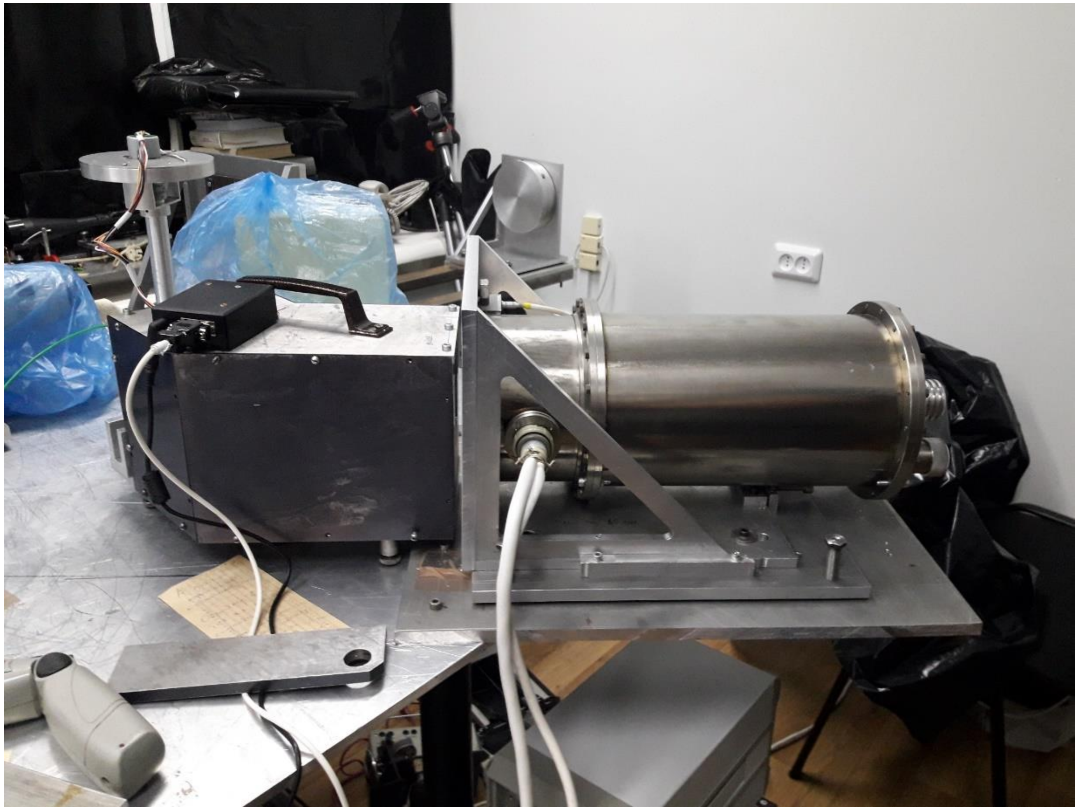


Solid model of the optomechanical design
of the spectrograph prototype:
a) general view; b) detailed view of the alignment mechanism.

Lab prototype assembly

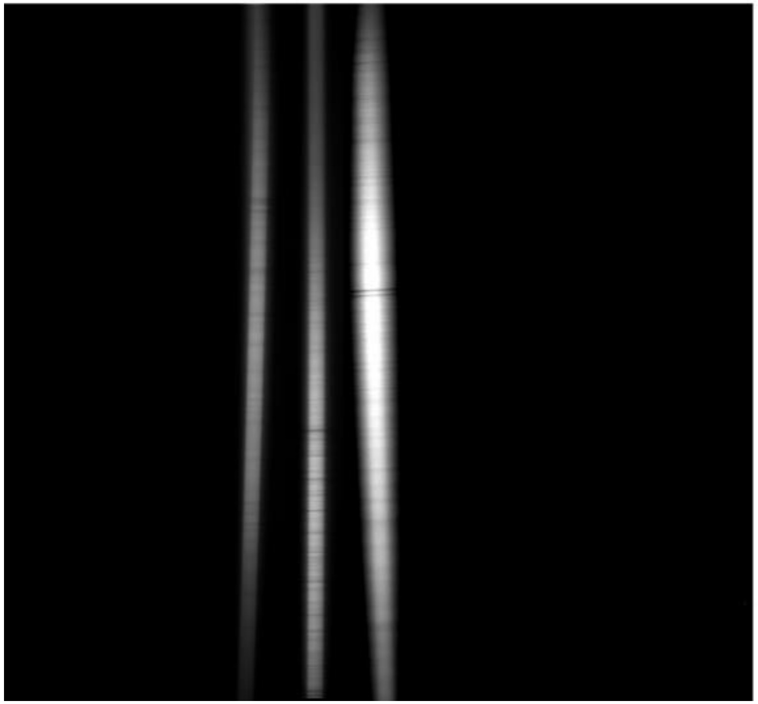


Assembled gratings unit.
From left to right: blue, green and red

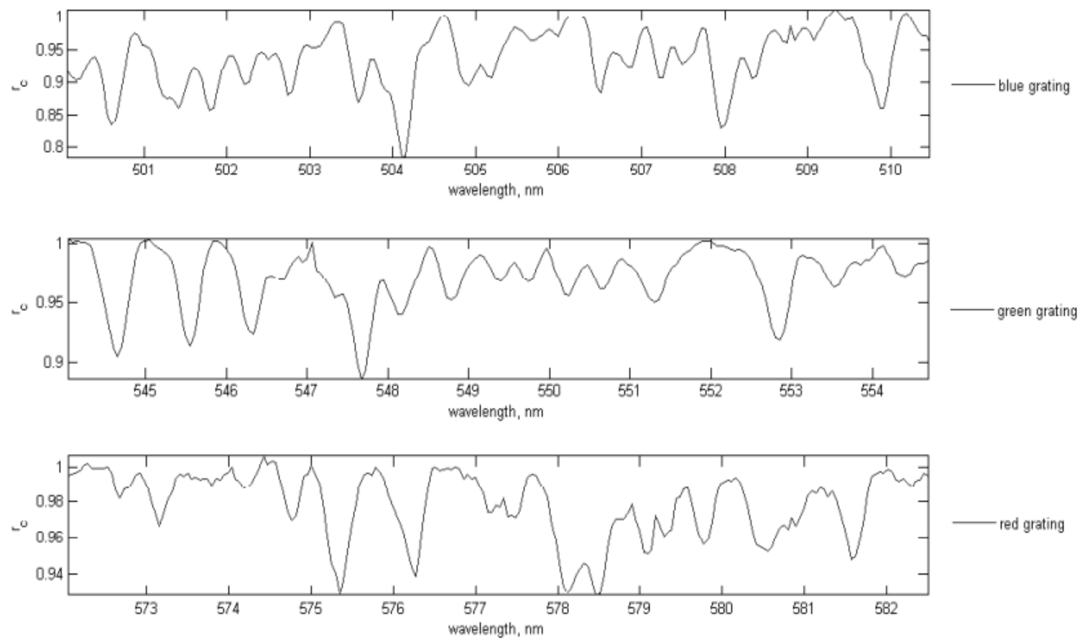


Entire spectrographs prototype
with camera attached

Experiments: spectral resolution



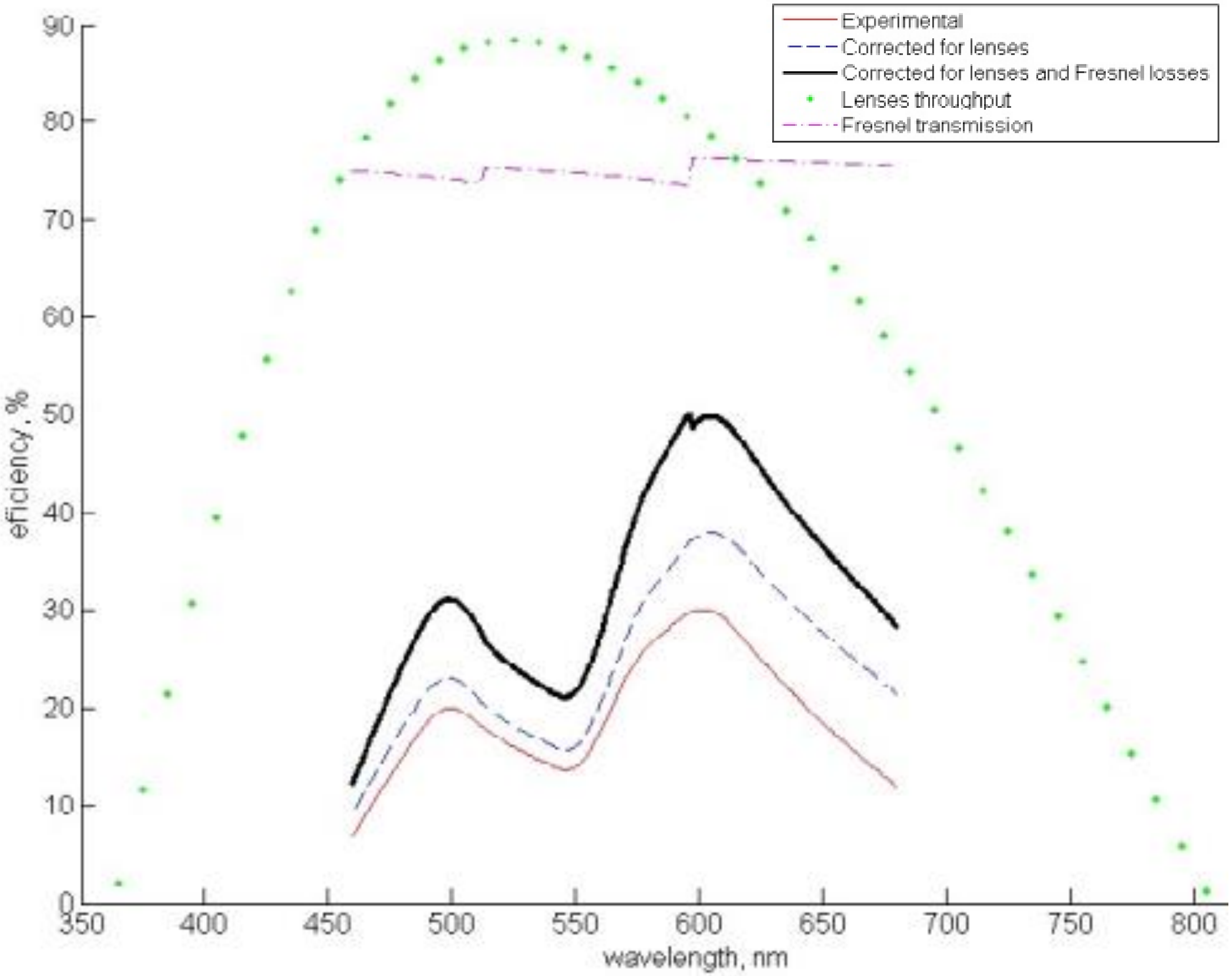
Solar spectrum image
from left to right:blue, green, and red



Fragments of normalized
wavelength-calibrated experimental solar spectra

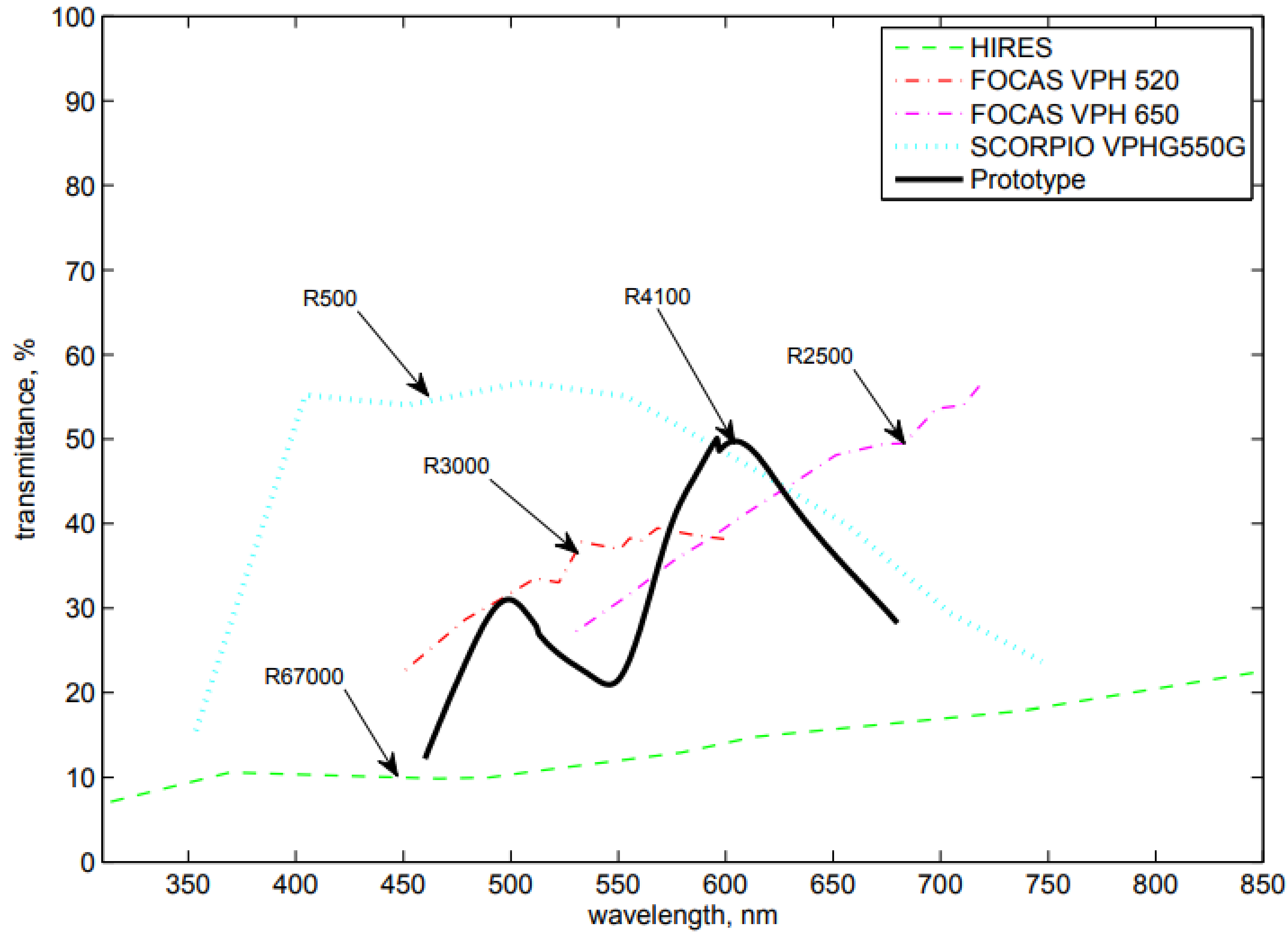
Band	Best measured resolution	Wavelength, nm
B	4100	500-510
G	2600	544-555
R	3500	572-582

Experiments: throughput (I)



Efficiency of individual optical parts
and reconstructed total efficiency of the spectrograph (black solid line).

Experiments: throughput (II)



Prototype throughput in comparison with existing instruments

Shortcomings

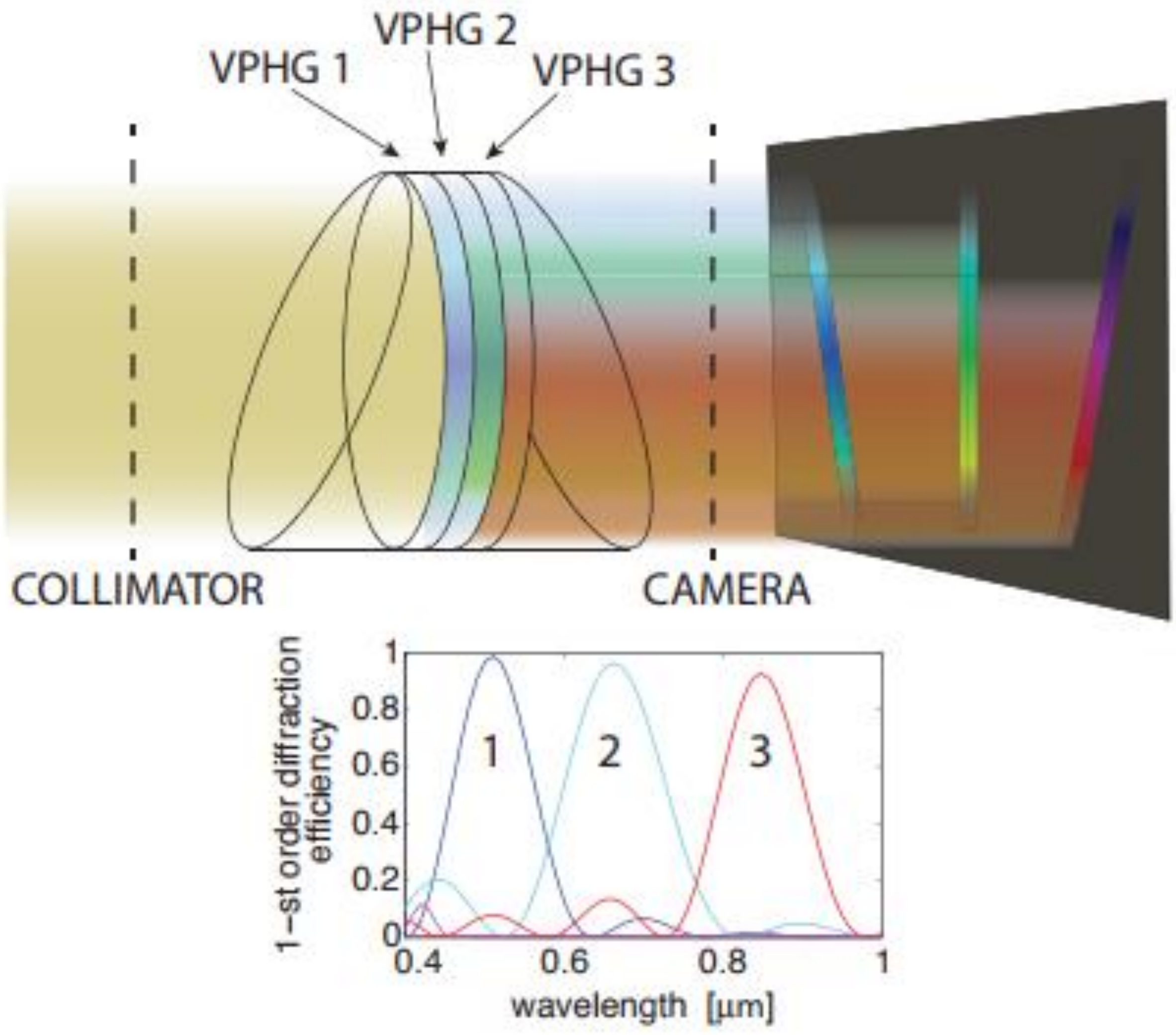
- Throughput due to the DE curves intersection
- Resolution and DE maxima conditions may contradict each other
- Difficult in alignment
- Reflection losses

✓ Rearrange the gratings in a red-to-blue order

✓ Move the complexity from the alignment stage to the manufacturing

✓ Decrease number of surfaces

Generation 2: multiplexed design



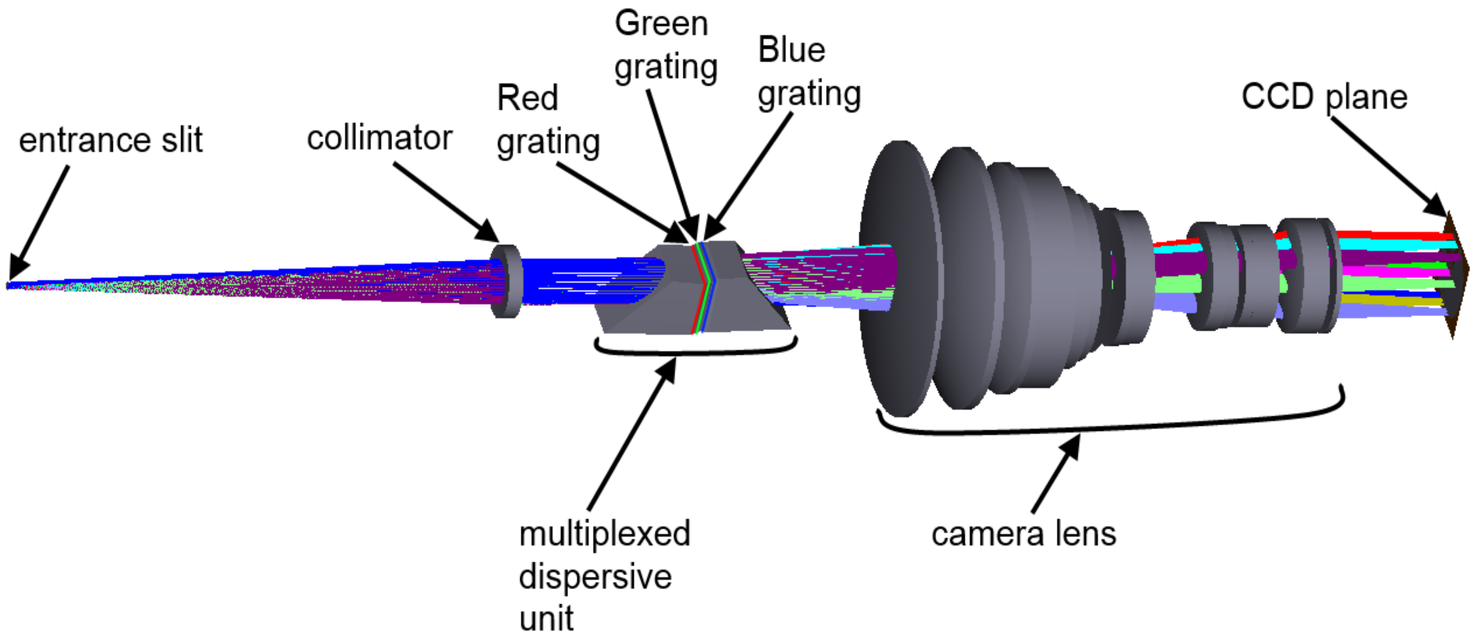
The multiplexed design principle:

Top - Scheme of a possible applic ation of a multiplexed device in GR ISM mode.

Bottom - the possible uncombined efficiencies, peaked in different sp ectral ranges.

* A. Zanutta & M. Landoni, M. Riva, and A. Bianco (Brera Observatry, INAF)

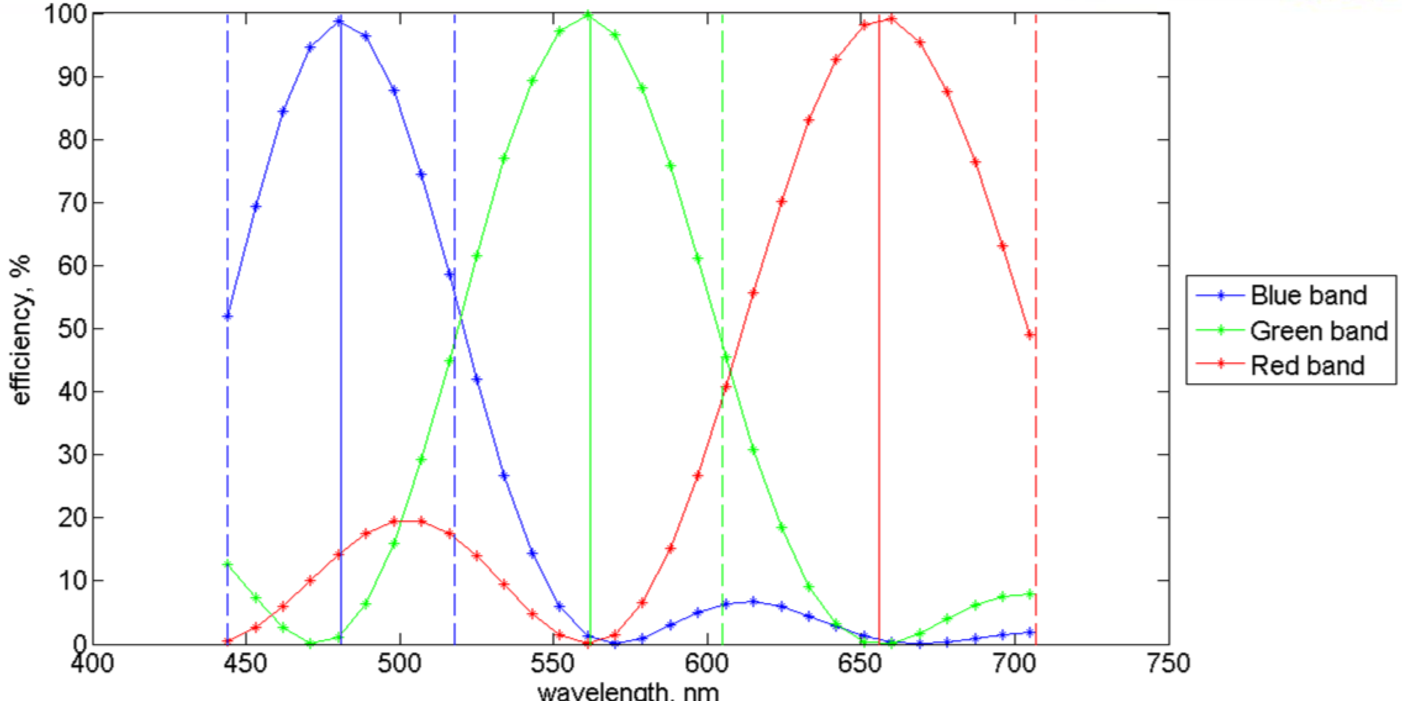
Multiplexed optical design



Optical scheme of the spectrograph with multiplexed disperser

Wavelength coverage	444-607 nm
Target spectral resolution	~5000
Entrance slit	0.034x3 mm
Collimator	Off-the-shelf achromatic doublet 200 mm
Camera	Commercial Canon lens 200 mm, F/2

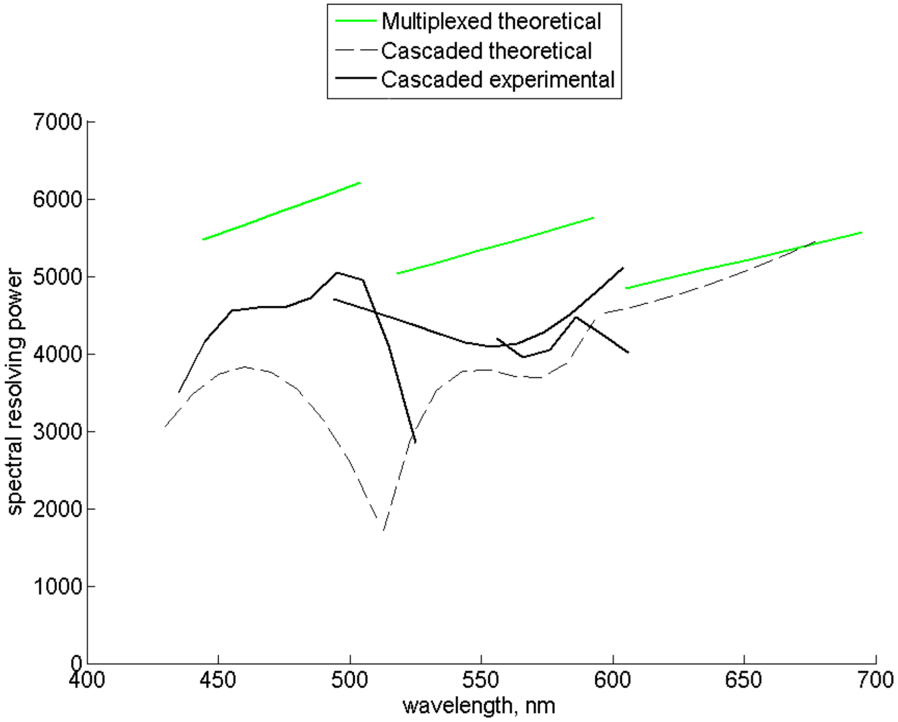
The multiplexed grism



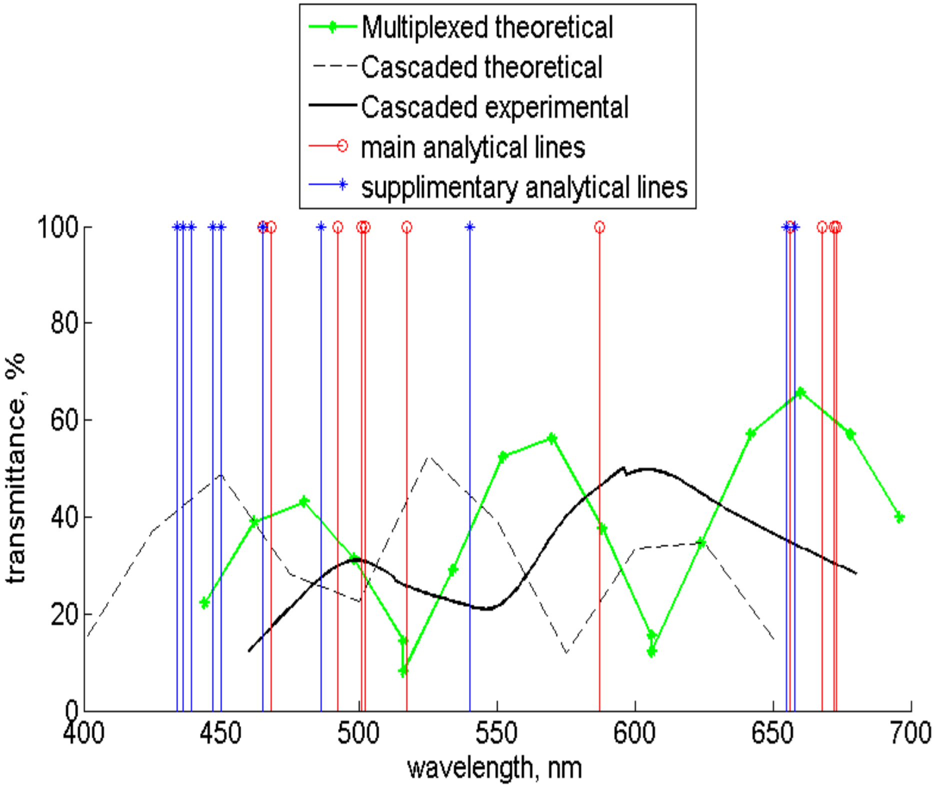
Diffraction efficiency of the customized VPH gratings
(recording in Bayfol™, absorbance ignored)

Grating	Spectral range	Frequency
Blue	444-518 nm	1349
Green	518-605 nm	1147
Red	605-707 nm	980
Prisms – 37.3 ° in fused silica		

Expected performance



Spectral resolution



Optical system throughput

Comparison with generation 1

Feature	Cascaded design		Multiplexed design	
Reflection losses	A lot of surfaces		Single dispersive element	
Image lines centering	Independent channels		Glued gratings, common prisms	
Efficiency/ resolution adjustment	Mutual contradictions		To be aligned once	
Diffraction efficiency optimization	Calibration and degradation issues (DCG)		Calibrated and stable (photopolymer)	
Analytical lines coverage	Blueshift		Perfect	
Resolution	Can be constant		Decreases in the red direction	
Manufacturing cost	Very low		Slightly higher	
Experimental proof	Yes		Coming soon	?

Prospective installation sites

Primary – Zeiss-1000 @ SAO RAS

Main mirror diameter	1016 mm
Ritchey - Cretien system:	
Focal length	13.3 m
Nonvignetted field diameter	170 mm = 45 arcmin
Wavelength range	0.3 - 10 mkm
Angular resolution	0.8 arcsec
Tube weight	4.8 tons
Total weight	12 tons
Maximum weight @ Cassegrain focus	96 kg
The limiting stellar mag.	23.5

Prospective – BTA @ SAO RAS

Main mirror diameter	6.05 m
Focal length	24 m
Light collecting area	25.1 sq.m
Wavelength range	0.3 - 10 mkm
Angular resolution	0.6 arcsec
Angular resolution	0.02 arcsec
Mass of the main mirror	42 tons
Total telescope mass	850 tons
Telescope height	42 m
Dome height	53 m

Other suggestions?

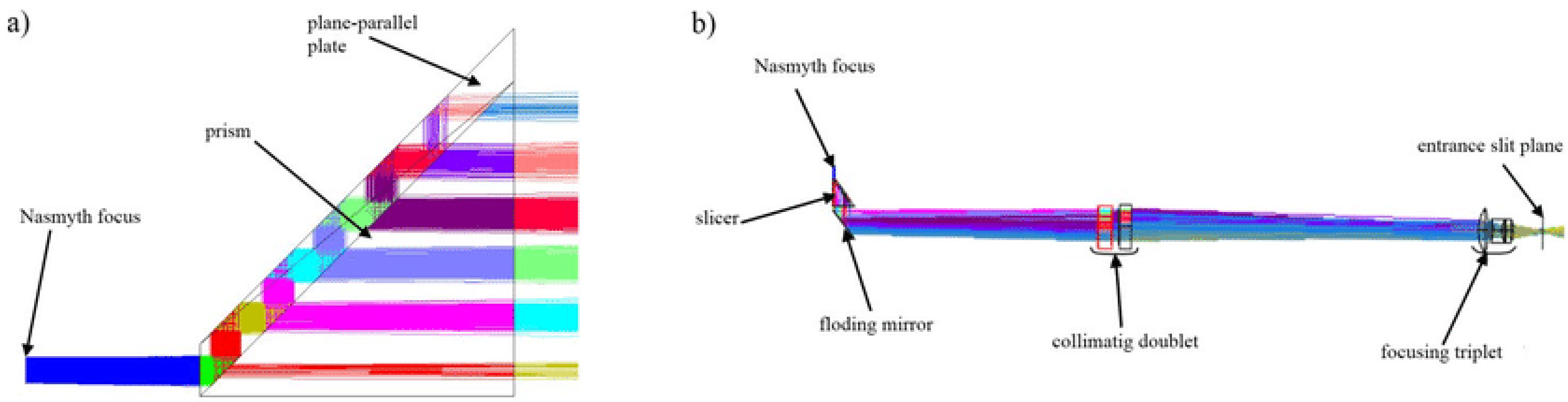
Scientific applications

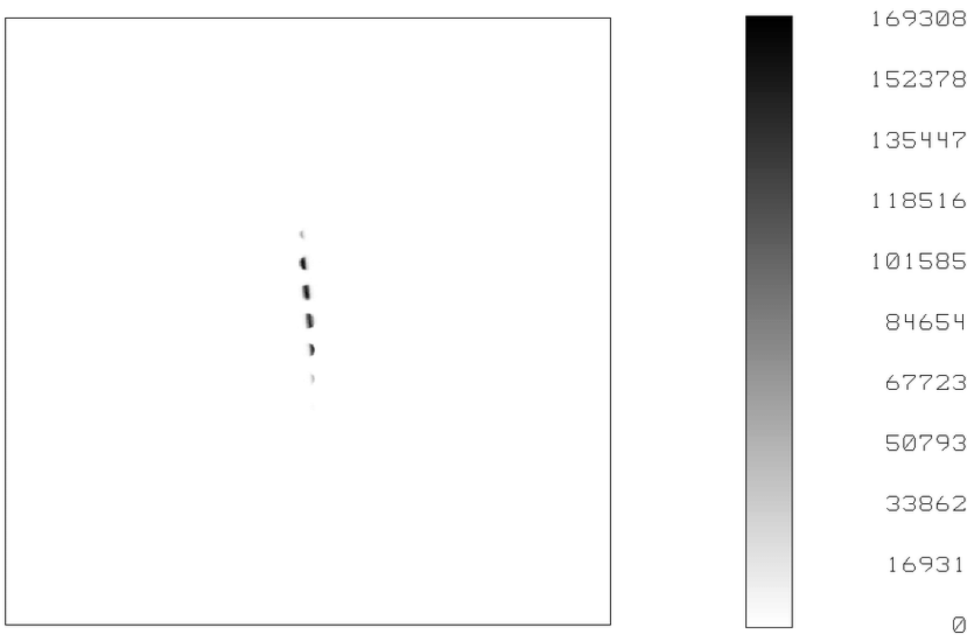
Objects, which can be studied with the spectrograph:

- LBV stars (Luminous Blue Variables), B[e]-supergiants and WR-stars
- Intermediate mass black holes (IMBHs)
- Faint, photometrically variable magnetic white dwarfs
- Exoplanets

Thank you for your attention!

Coupling with telescope

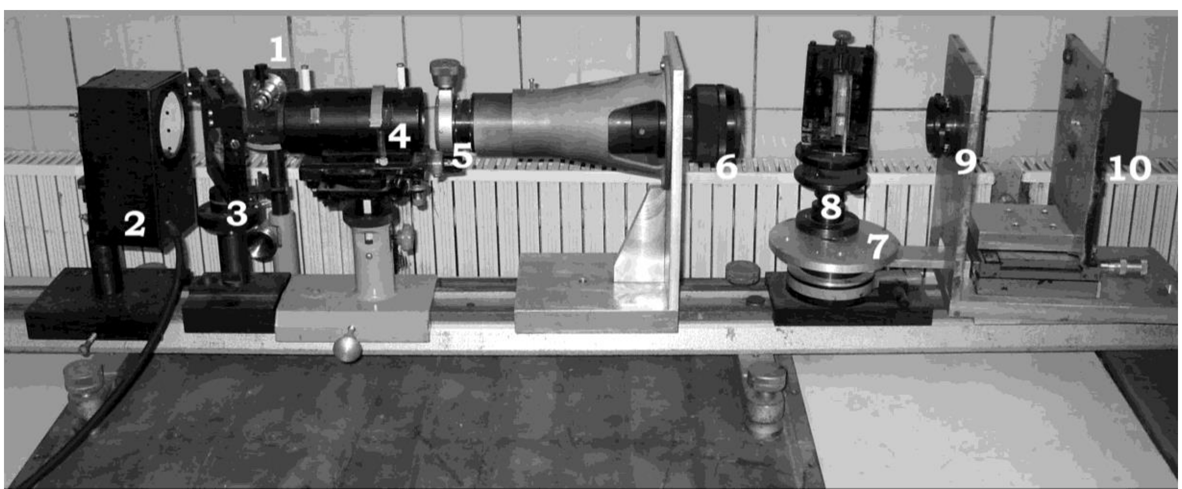




Top –(a) image slicer design based on TIR
(b) focal reducer design.

Bottom – simulation of the sliced and scaled image

Gratings fabrication



Equipment for
(a) fabrication and
(b) testing of VPH gratings at State Inst. Of Applied Optics (Kazan)