Key Requirement Parameters for dispersion elements in optical/NIR spectrometers

Colin Cunningham

UK Astronomy Technology Centre

& Edinburgh, Glasgow & Heriot Watt Universities

Horizon 2020
European Union Funding
for Research & Innovation

N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

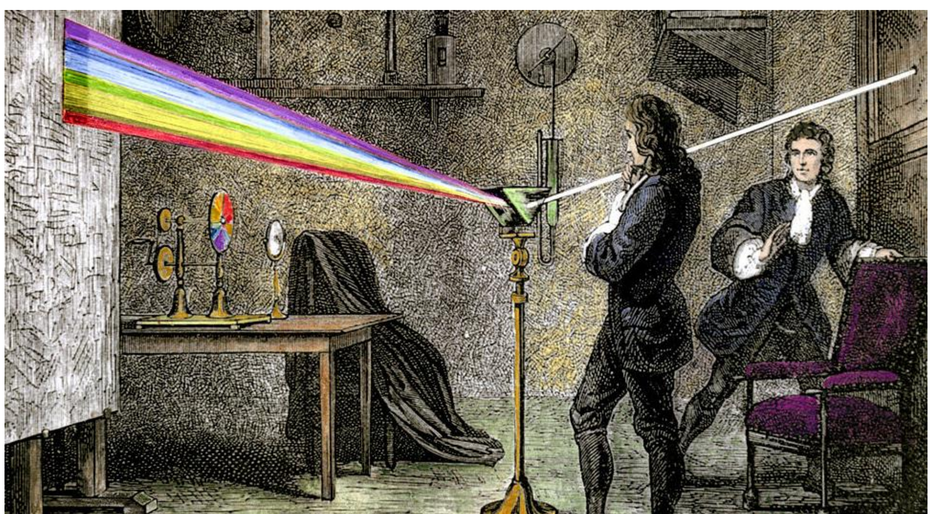
(3075) Numb. 80.

PHILOSOPHICAL TRANSACTIONS.

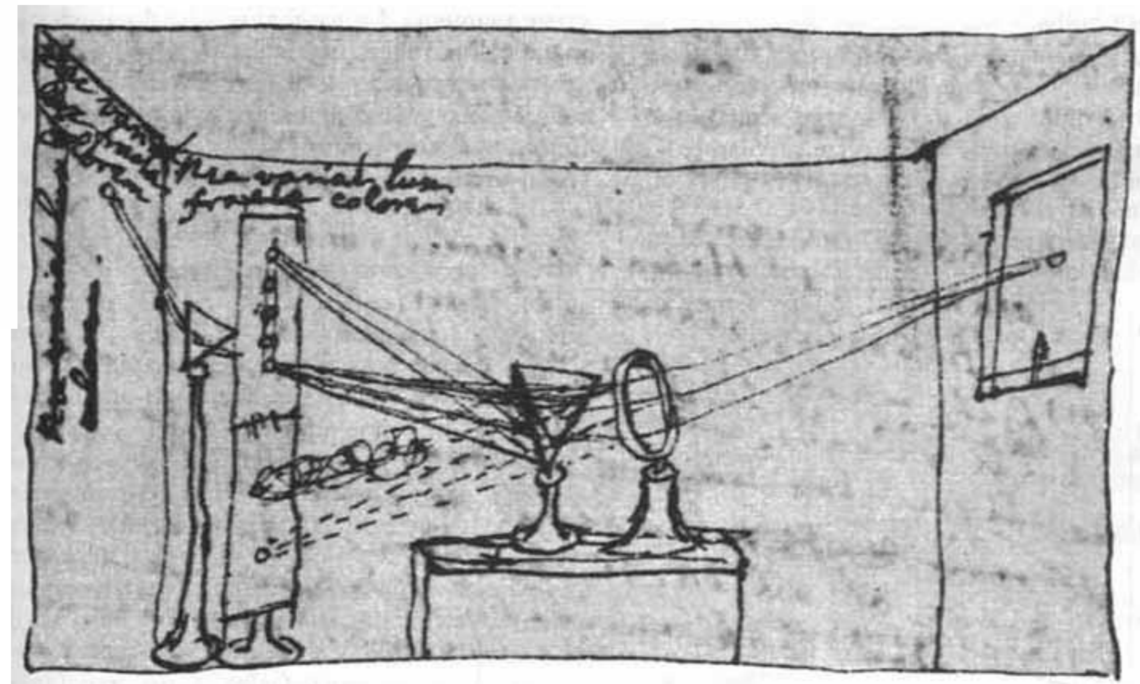
February 19. 16$\frac{71}{72}$.

The CONTENTS.

A Letter of Mr. Isaac Newton, *Mathematick Professor in the University of Cambridge; containing his New Theory about* Light *and* Colors: *Where* Light *is declared to be not Similar or Homogeneal, but consisting of difform rays, some of which are more refrangible than others:* And Colors *are affirm'd to be not Qualifications of Light, deriv'd from Refractions of natural Bodies, (as 'tis generally believed;) but Original and Connate properties, which in divers rays are divers: Where several Observations and Experiments are alledged to prove the said Theory. An Accompt of some Books:* I. *A Description of the*



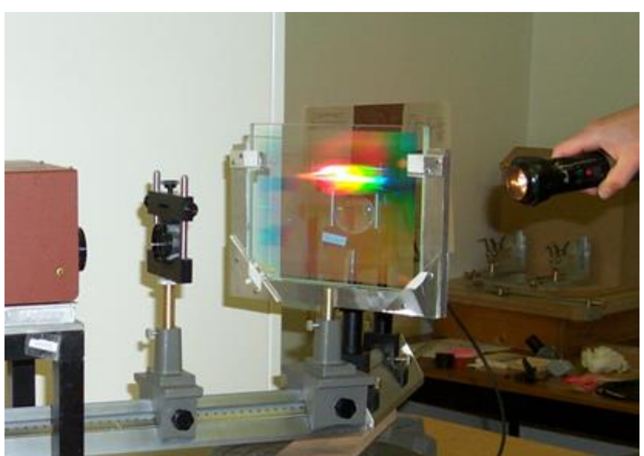
Isaac Newton 1672

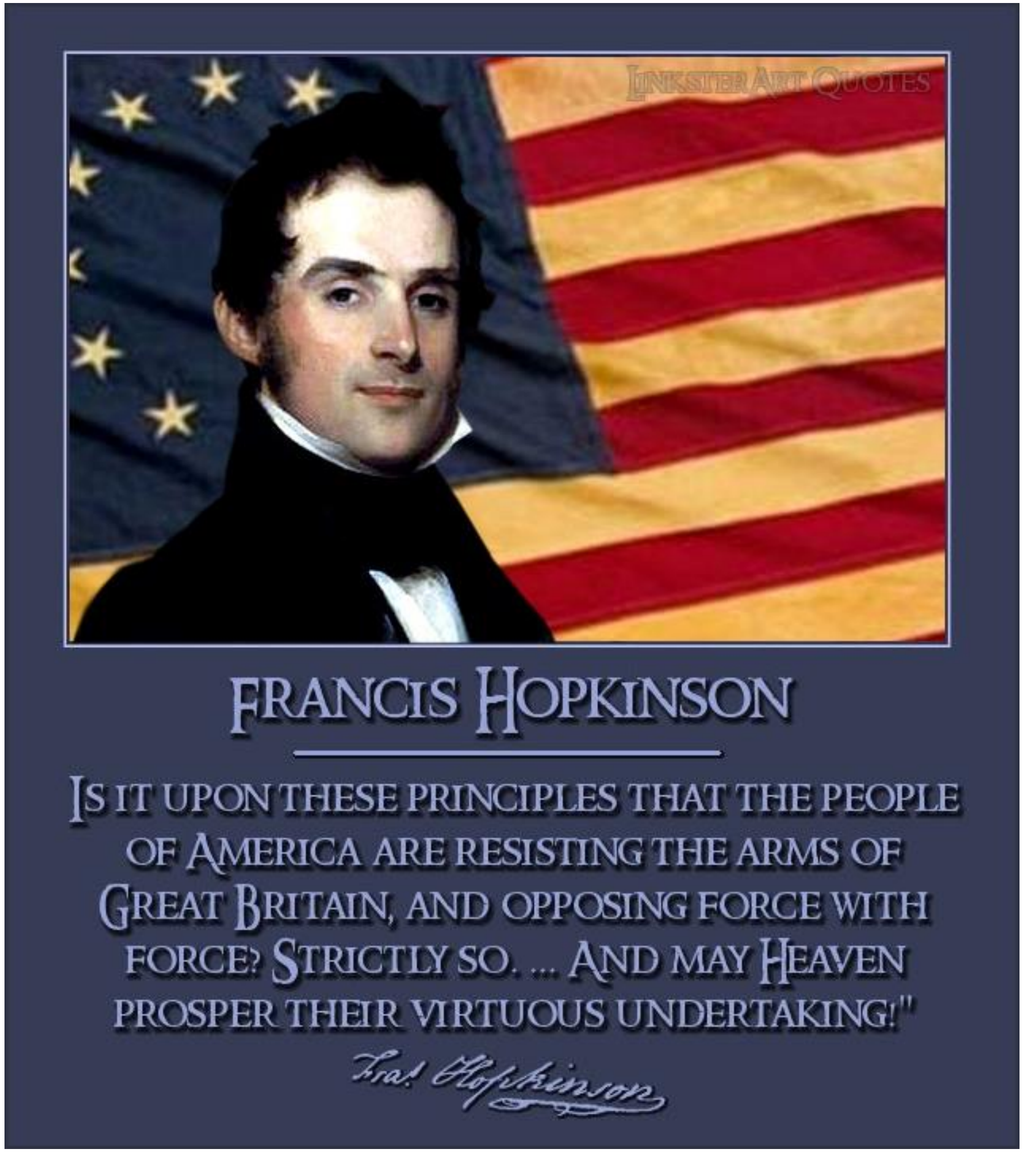


James Gregory 1688 in St Andrews Scotland

If ye think fit, ye may signify to Mr. Newton a small experiment, which (if he know it not already) may be worthy of his consideration. Let in the sun's light by a small hole to a darkened house, and at the hole place a feather, (the more delicate and white the better for this purpose,) and it shall direct to a white wall or paper opposite to it a number of small circles and ovals, (if I mistake them not,) whereof one is somewhat white, (to wit, the middle, which is opposite to the sun,) and all the rest severally coloured. I would gladly hear his thoughts of it.

Correspondence of Scientific Men of the Seventeenth Century ..., Volume 2
By Stephen Jordan Rigaud





N° XXIV.

An Optical Problem, propoſed by Mr. HOPKINSON, *and ſolved by* Mr. RITTENHOUSE.

Philadelphia, March 16th, 1785.

DEAR SIR,

Read Feb. 17, 1786.

I TAKE the liberty of requeſting your attention to the following problem in *optics*. It is I believe entirely new, and the ſolution will afford amuſement to you and inſtruction to me.

Setting at my door one evening laſt ſummer, I took a ſilk handkerchief out of my pocket, and ſtretching a portion of it tight between my two hands, I held it up before my face and viewed, through the handkerchief, one of the ſtreet lamps which was about one hundred yards diſtant; expecting to ſee the threads of the handkerchief much magnified. Agreeably to my expectation I obſerved the ſilk threads magnified to the ſize of very coarſe wires; but was much ſurpriſed to find that, although I moved the handkerchief to the right and left before my eyes, the dark bars did not ſeem to move at all, but remained permanent before the eye. If the dark bars were occaſioned by the interpoſition of the magnified threads between the eye and the flame of the lamp, I ſhould have ſuppoſed that they would move and ſucceed each other, as the threads were made to move and paſs in ſucceſſion before the eye; but the fact was otherwiſe.

To account for this phenomenon exceeds my ſkill in *optics*. You will be ſo good as to try the experiment, and if you find the caſe truly ſtated, as I doubt not you will, I ſhall be much obliged by a ſolution on philoſophical principles. I am ſir, with great ſincerity,

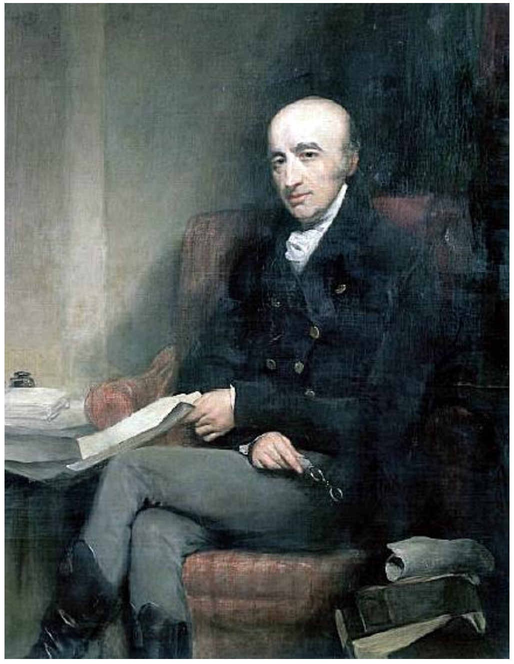
Your moſt effectionate friend,
And very humble ſervant,
F. HOPKINSON.

David Rittenhouse 178

Rittenhouse made perhaps the
first diffraction grating using 50 hairs
between two finely threaded screws, with an
approximate spacing of about 100 lines per
inch

I was ſurprized to find that the red rays are more bent out of their firſt direction, and the blue rays leſs; as if the hairs acted with more force on the red than on the blue rays, contrary to what happens by refraction, when light paſſes obliquely through the common ſurface of two different mediums. It is, however, conſonant to what Sir Iſaac Newton obſerves with reſpect to the fringes that border the ſhadows of hairs and other bodies; his words

William Wollaston 1802



Observed dark lines in the spectrum of the Sun

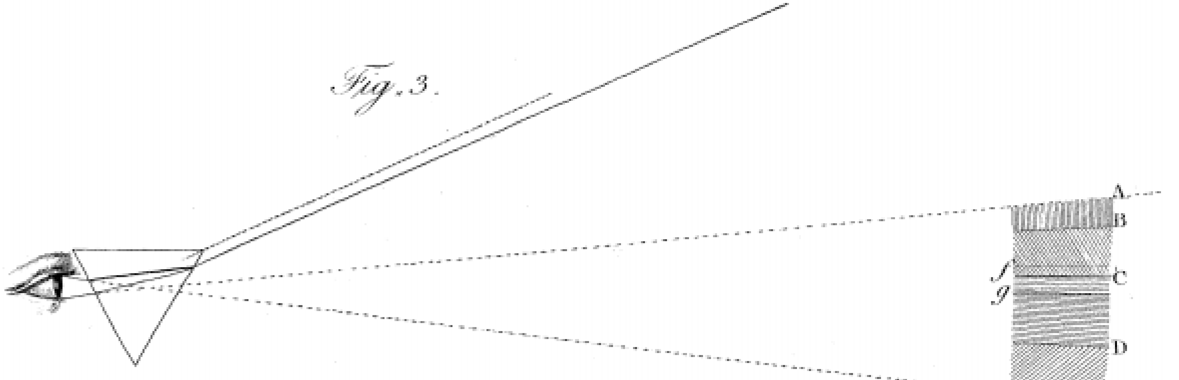
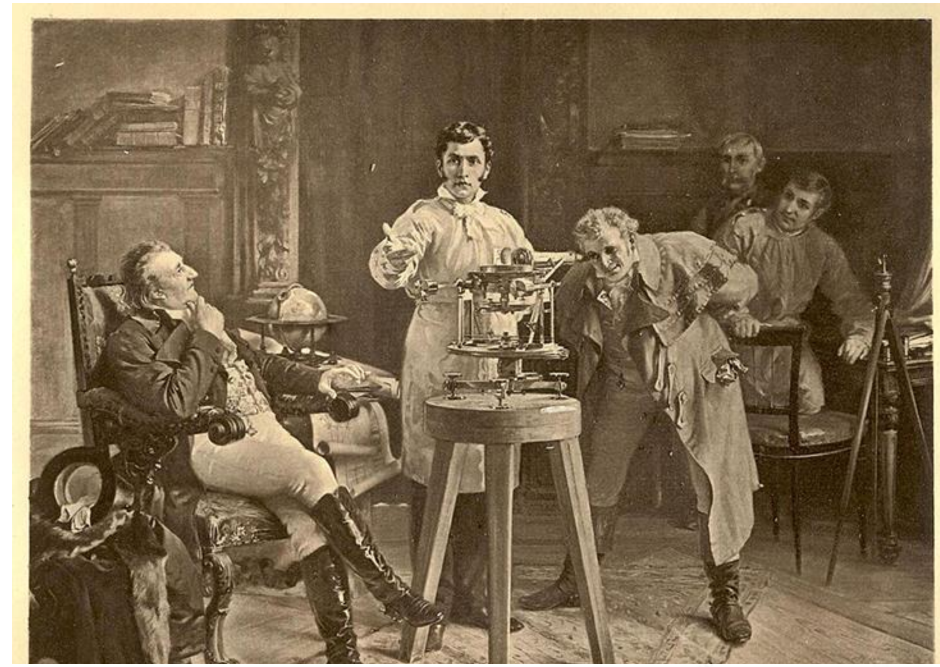
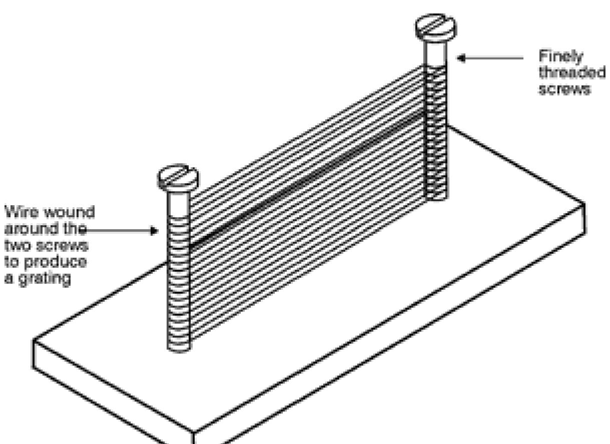
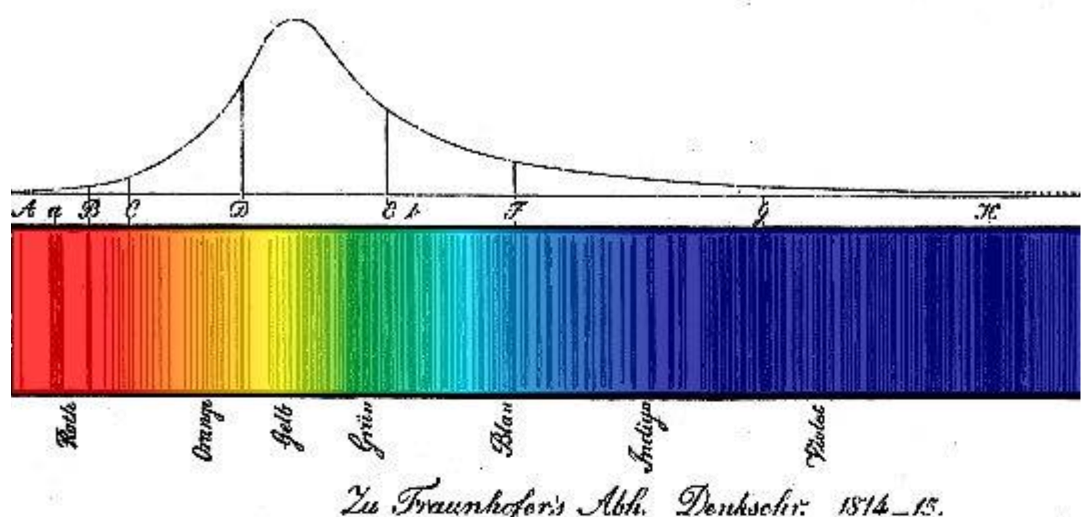


Fig. 3.

Joseph von Fraunhofer 1814







Basic Physics

Measurement of the wavelength (or frequency) of light

- Direct measurement of frequency – fundamental property if light
  - Frequency Counting eg Spectrum analyser – up to 100GHz
  - Energy Measurement

$$E=h\nu$$

Good for x-rays with CCDs and microwaves etc with superconducting devices

- Wavelength Measurement by Interference through phase delays

$\lambda= c\nu$, and c varies with material light propagates through

ν does not change at a refractive boundary, as Photon energy is conserved, but the velocity of light varies with wavelength in some media = DISPERSION

This talk will be about Prisms, Gratings and Grisms

Wavelength measurement methods not covered today:

- Fabry-Perot interferometer
- Fourier Transform Spectrometer
- Digital Planar Holography

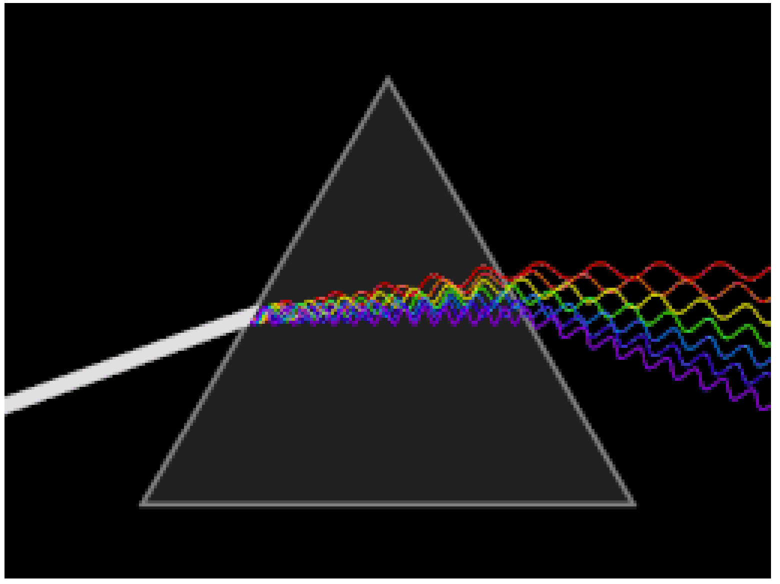
Dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency

- *Chromatic dispersion* refers to bulk material dispersion, that is, the change in refractive index with optical frequency

- In a waveguide there is also the phenomenon of *waveguide dispersion*, in which case a wave's phase velocity in a structure depends on its frequency simply due to the structure's geometry

If light of different wavelengths is deviated by a grating or prism through different angles, θ, the rate of change of θ with wavelength, $\mathbf{d\theta/d\lambda}$ is the angular dispersion

Prisms



- Dispersion is not linear, increasing towards shorter wavelengths
- Prism dispersion is not very high – often two or three prisms were used in tandem to increase this
- Glass absorbs ultraviolet and infrared light – quartz or fused silica are necessary outside visible wavelengths
- Light losses occur at both surfaces (more if more than one prism is used) and in the glass

Prism Dispersion

Hartmann dispersion formula:

$$\mu_\lambda = A + \frac{B}{\lambda - C}$$

It can be derived that

$$\frac{d\theta}{d\lambda} \propto (\lambda - C)^{-2}$$

So dispersion is very non-linear,
Tyically 5x at 400nm than 700nm

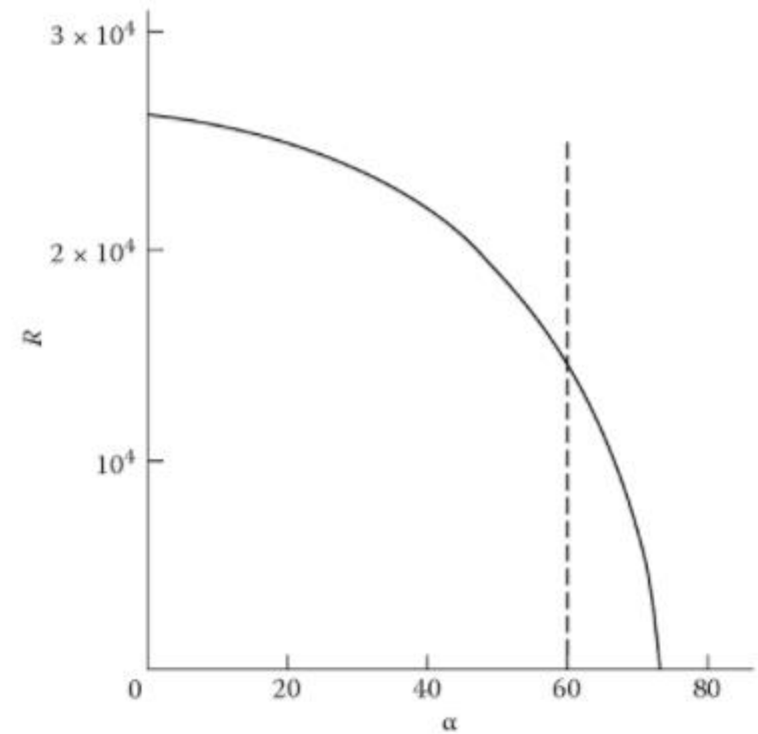
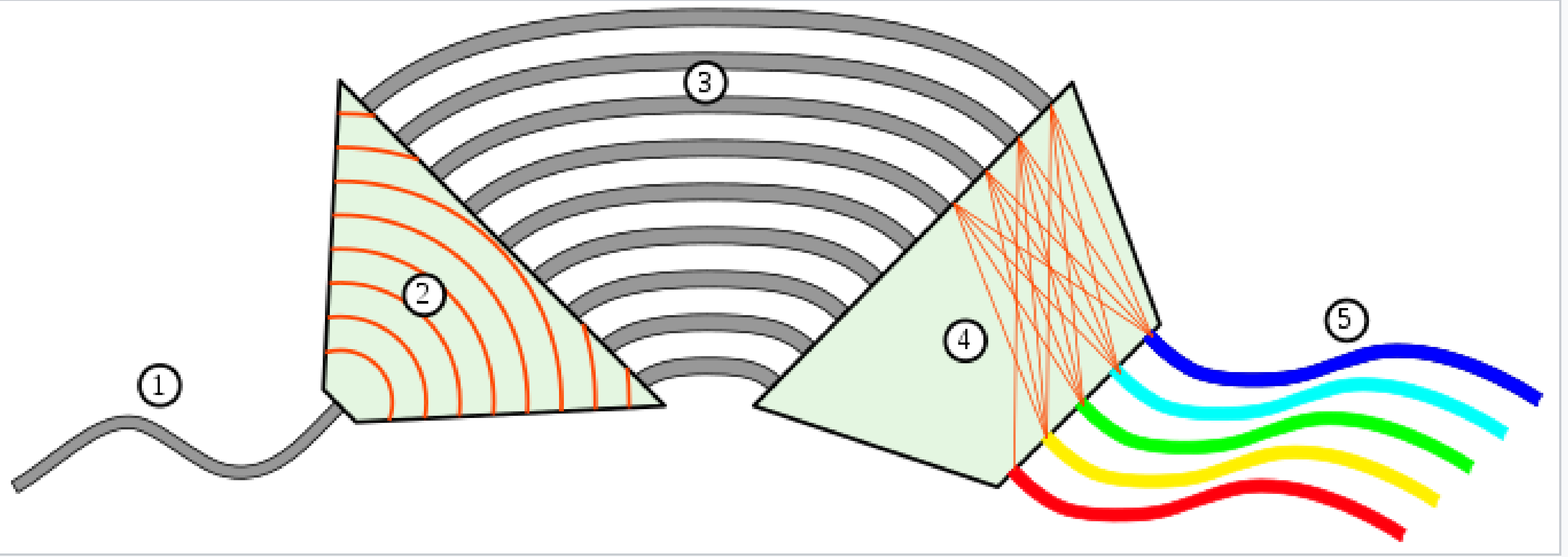


FIGURE 4.13 Resolution of a dense flint prism with a side length of 0.1 m at a wavelength of 500 nm, with changing apex angle α.

Astrophysical Techniques, Sixth Edition
By C.R. Kitchin

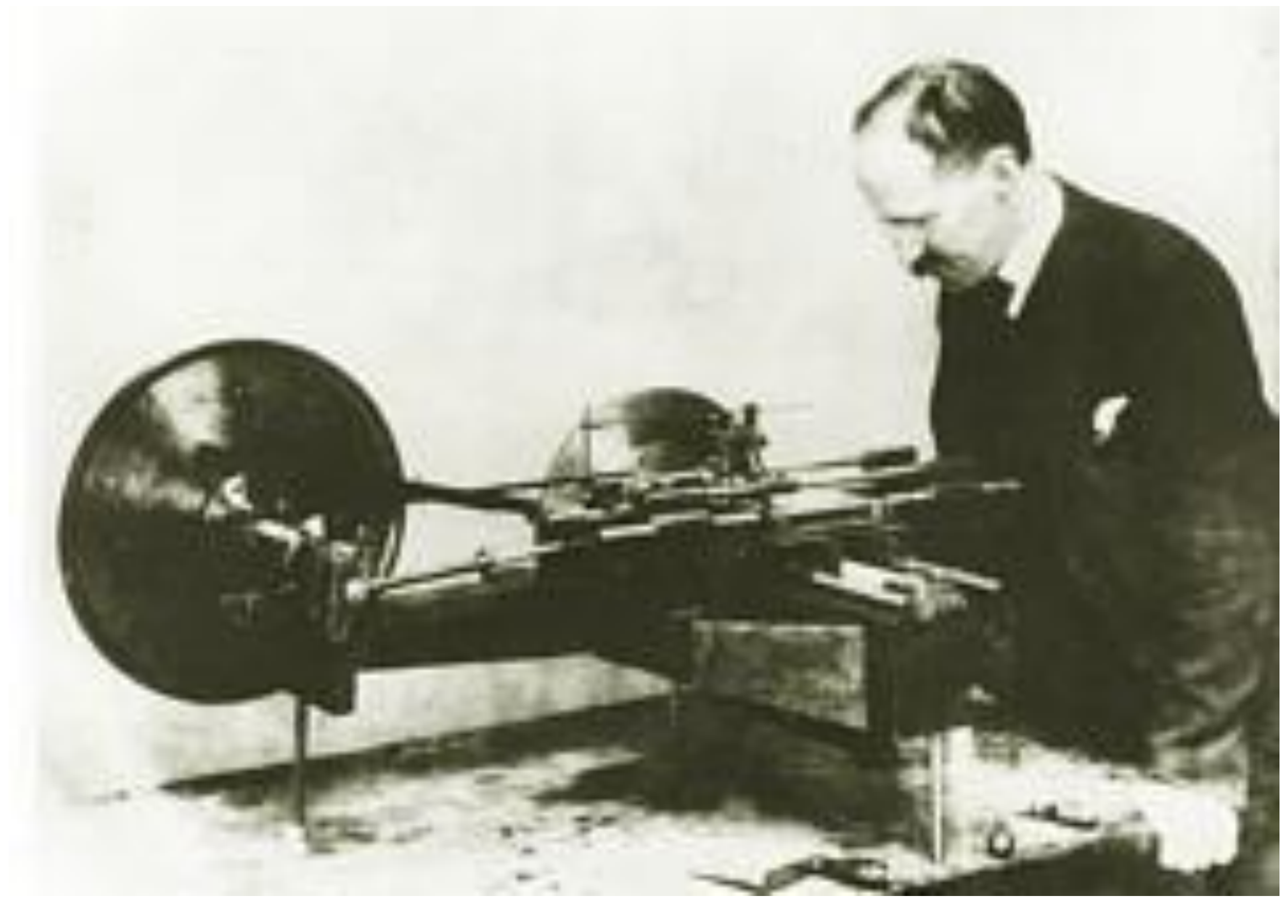
Arrayed Waveguide Grating



The incoming light **(1)** traverses a free space **(2)** and enters a bundle of optical fibers or channel waveguides **(3)**. The fibers have different length and thus apply a different phase shift at the exit of the fibers. The light then traverses another free space **(4)** and interferes at the entries of the output waveguides **(5)** in such a way that each output channel receives only light of a certain wavelength. The orange lines only illustrate the light path. The light path from **(1)** to **(5)** is a demultiplexer, from **(5)** to **(1)** a multiplexer.

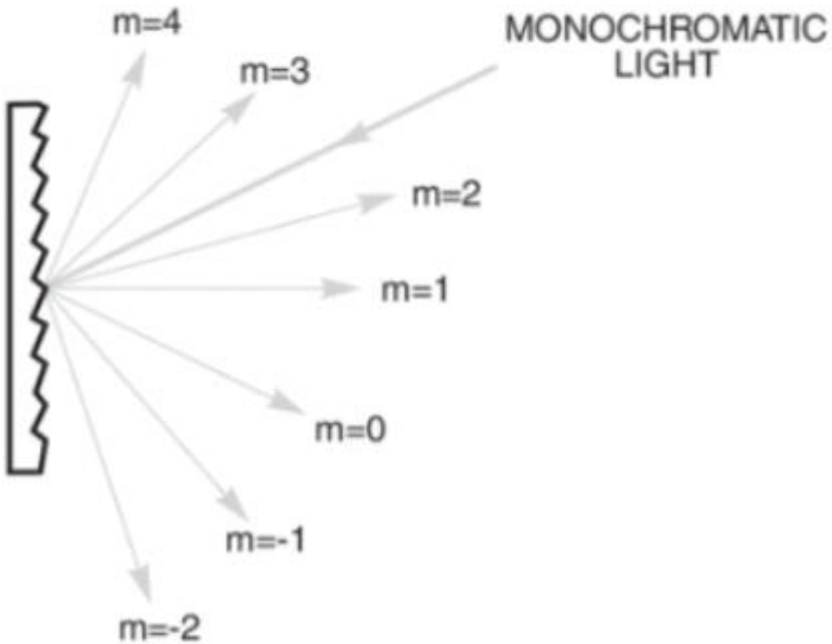
Wikimedia Commons: Dr. Schorsch

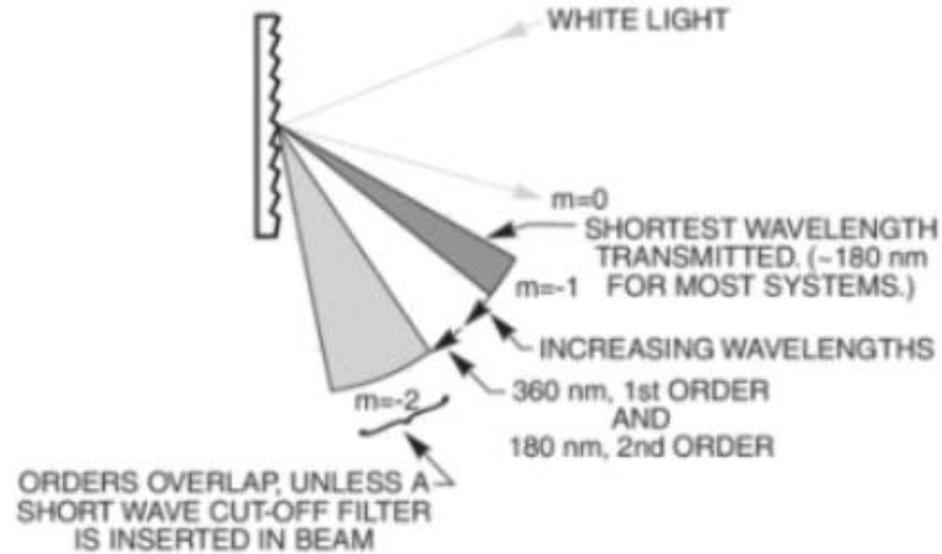
1882: Henry Rowland's improved Ruling Engine



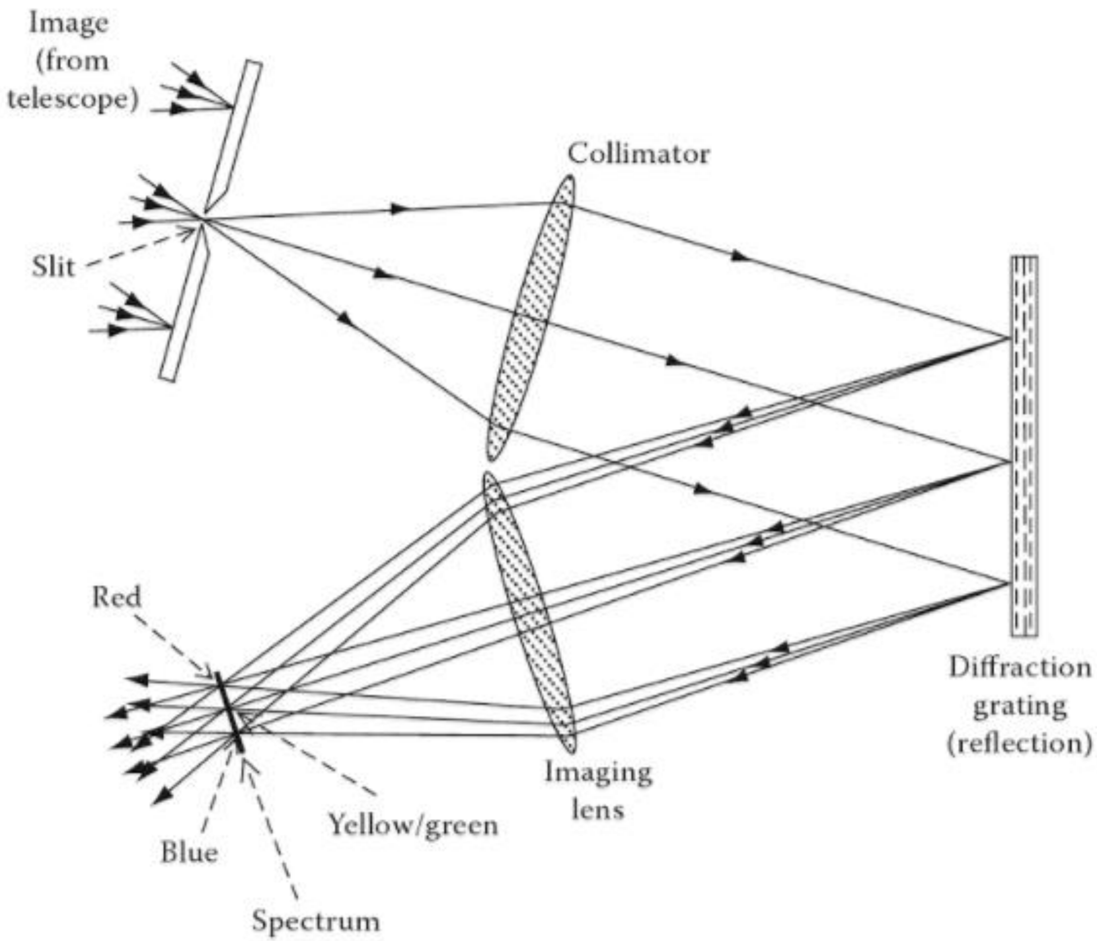
Johns Hopkins University

Reflection gratings





Grating Spectrometer



Linear dispersion is

$$\frac{dx}{d\lambda} = f_2 \frac{d\theta}{d\lambda}$$

Where f2 is the F# of the camera

m = order, d= grating spacing

$$\frac{dx}{d\lambda} = \pm \frac{mf_2}{d\cos\theta}$$

Now since θ varies very little over an individual spectrum, we may write

$$\frac{dx}{d\lambda} \approx \text{constant} \qquad 10^{-7} < \frac{d\lambda}{dx} < 5\times10^{-5}$$

C.R. Kitchin, Astrophysical Techniques

Blazed Gratings

Blaze: The concentration of a limited region of the spectrum into any order other than the zero order
Blazed gratings are manufactured to produce maximum efficiency at designated wavelengths

$$\sin \alpha + \sin \beta = kn\lambda_B 10^{-6}$$

$\omega = \alpha = \beta$ where ω = the blaze angle

$$2 \sin \omega = kn\lambda_B 10^{-6}$$

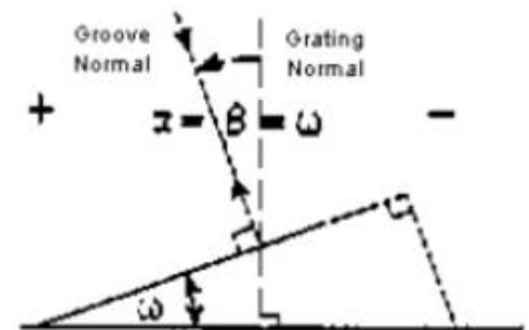
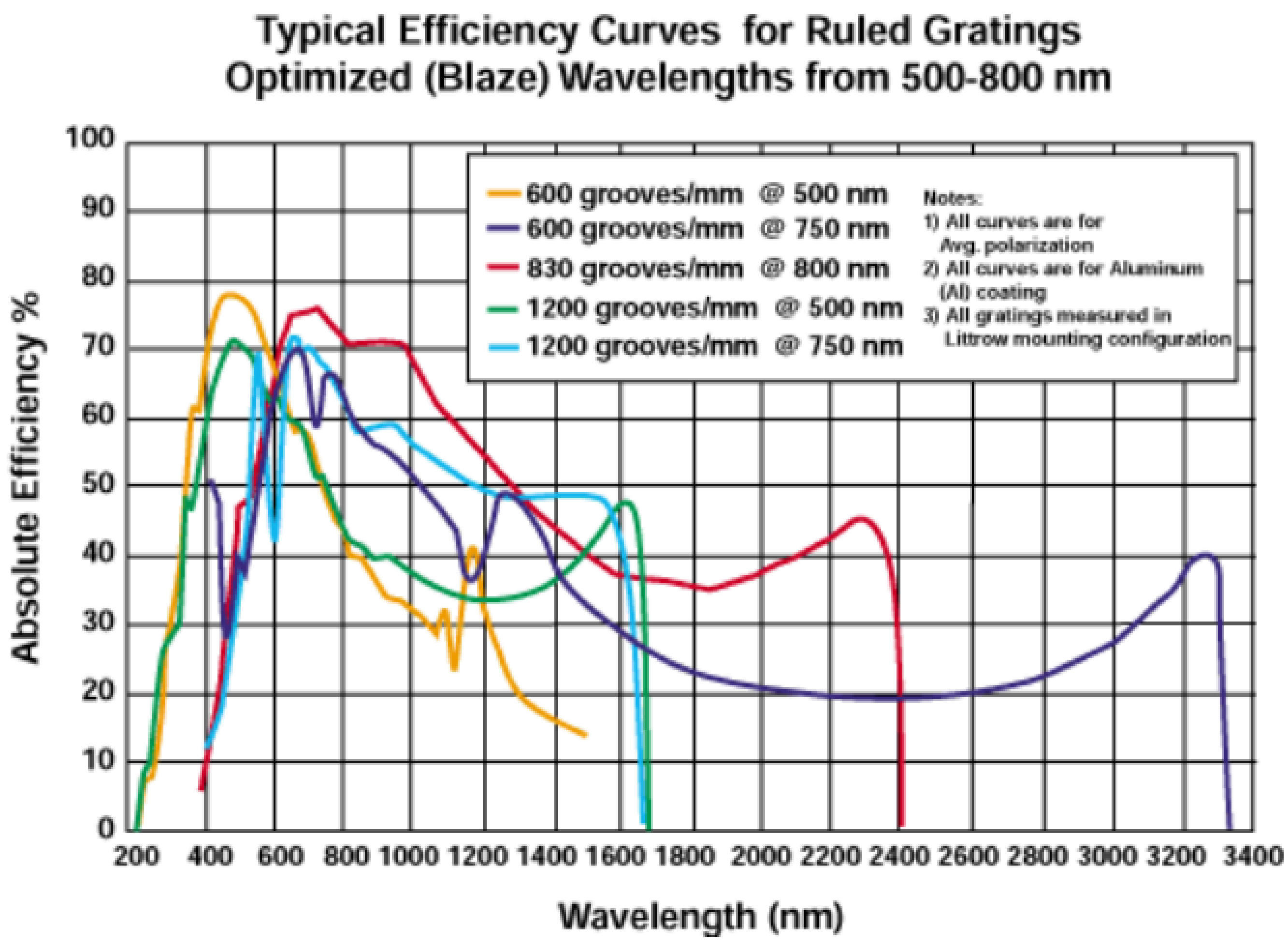


Figure 4 - Littrow Condition for a Single Groove of a Blazed Grating

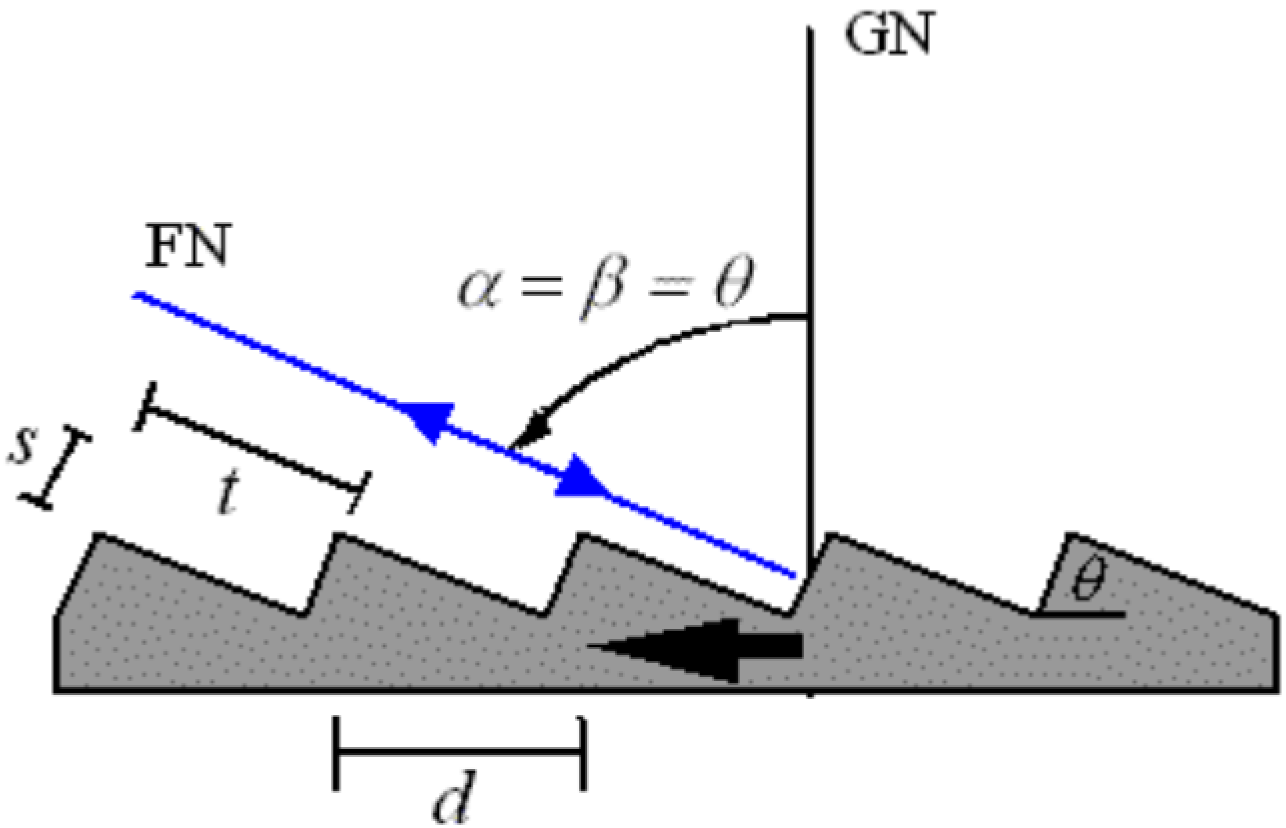


Edmund Optics Catalogue

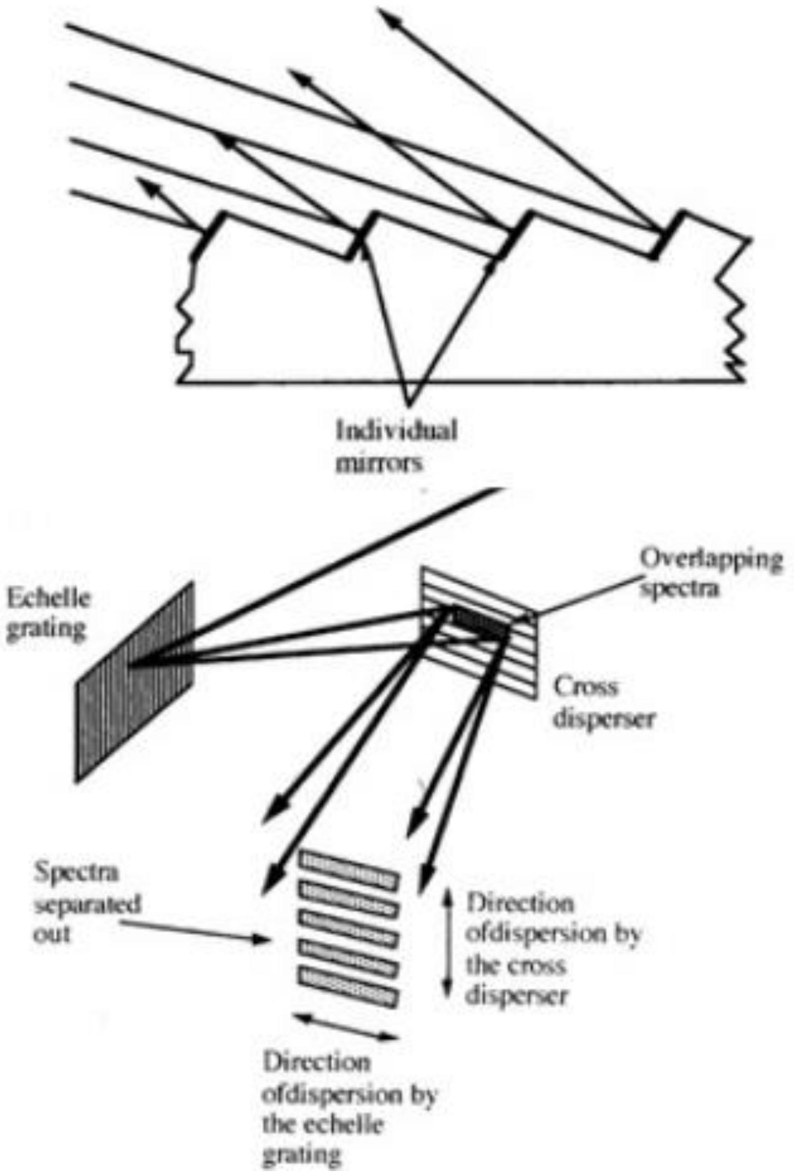
Echelle Grating

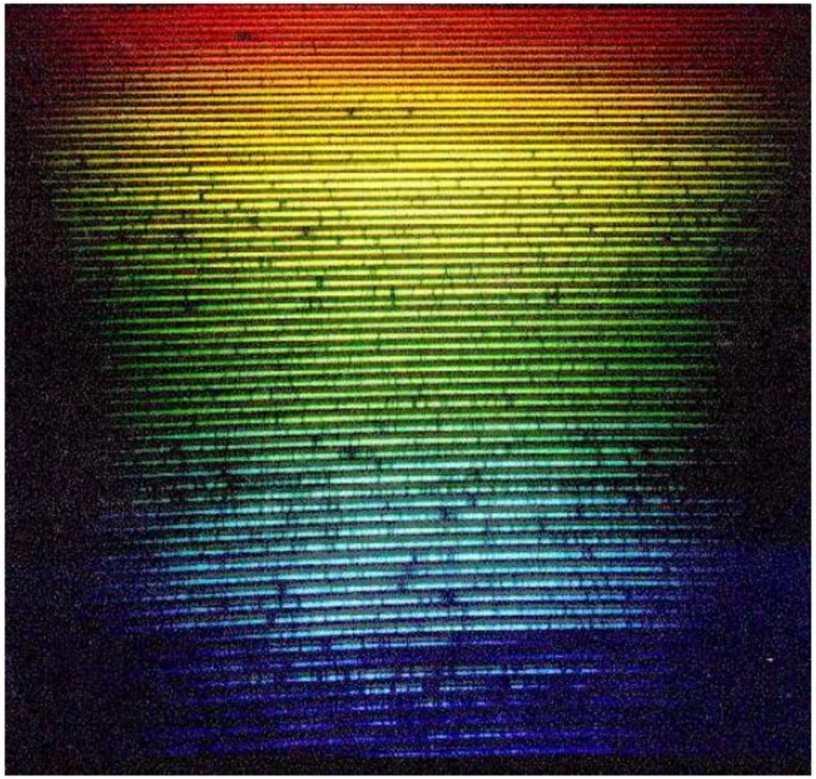
$\Delta\beta/\Delta\lambda = m/d \cos\beta$

If m is ~ 100, we have high resolution with coarse gratings



Cross dispersed Echelle



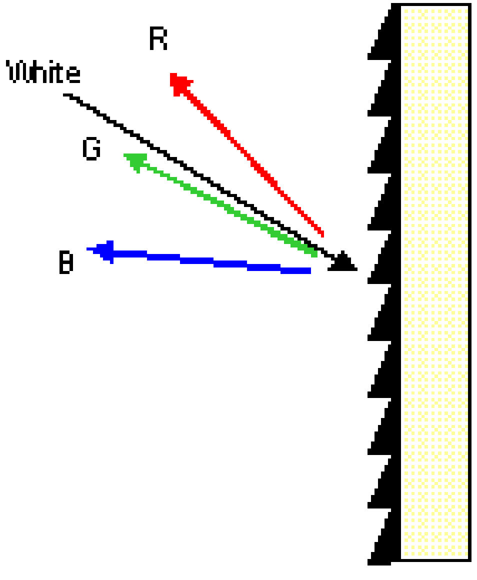


Echelle spectrum from the FOCES instrument at Calar Alto Observatory. Image from www.usm.uni-muenchen.de/people/ gehren/foces.html.

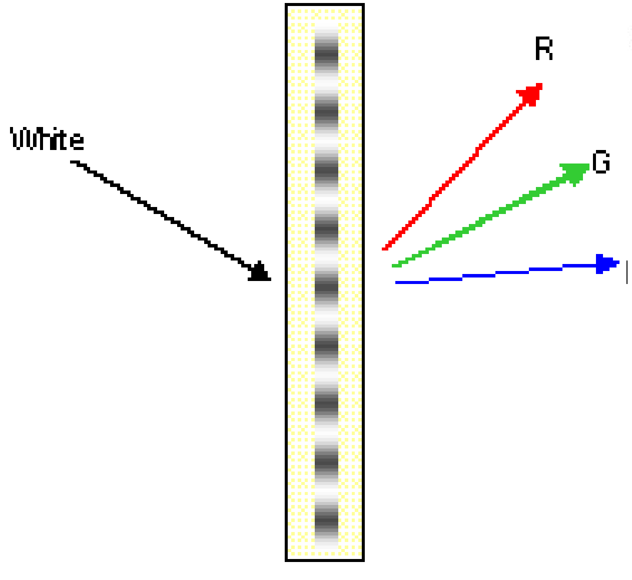
C.R. Kitchin, Optical Astronomical Spectroscopy

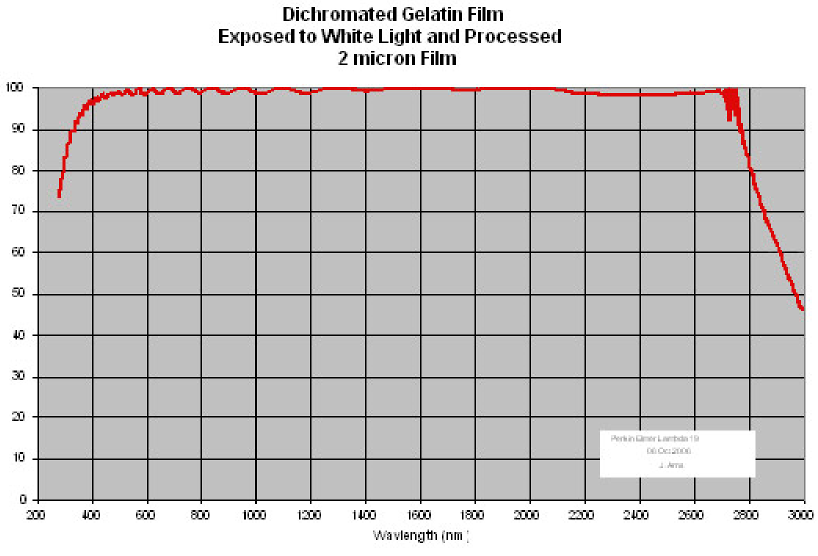
Volume Phase Holographic Gratings

Conventional Surface
Relief Reflection Grating



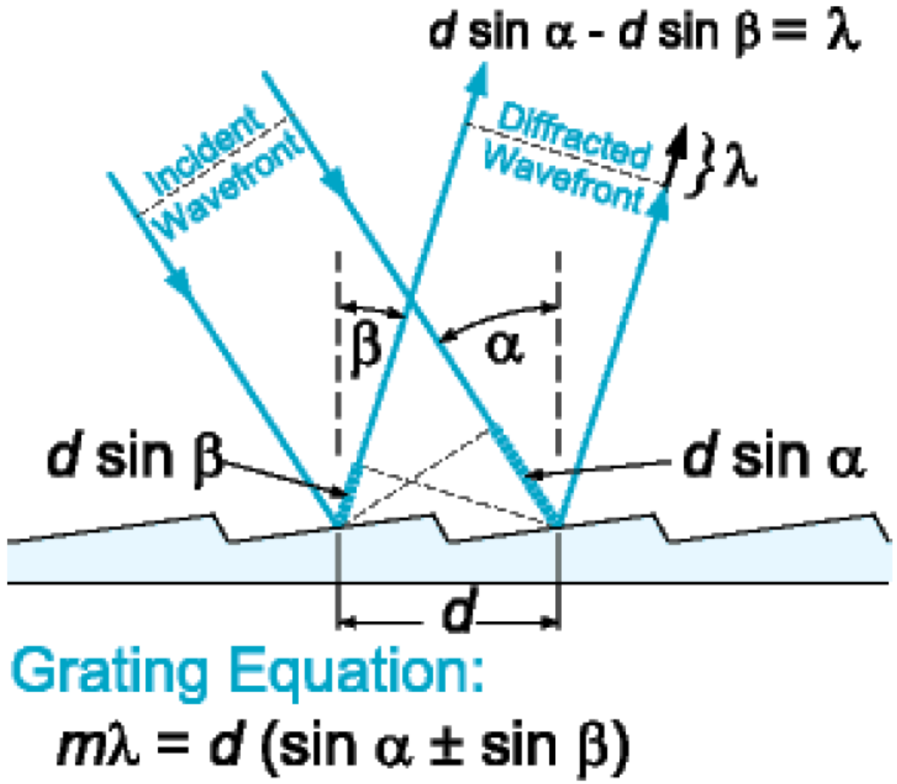
Volume Phase Holographic
(VPH) Transmission Grating





Kaiser Optical Systems Inc.

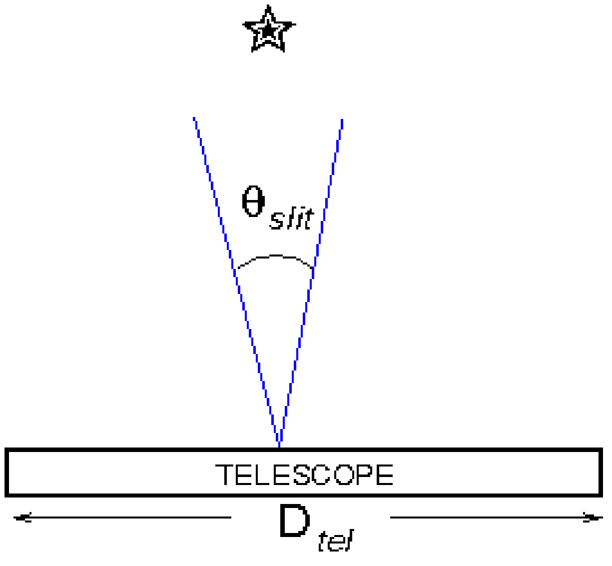
Grating equation



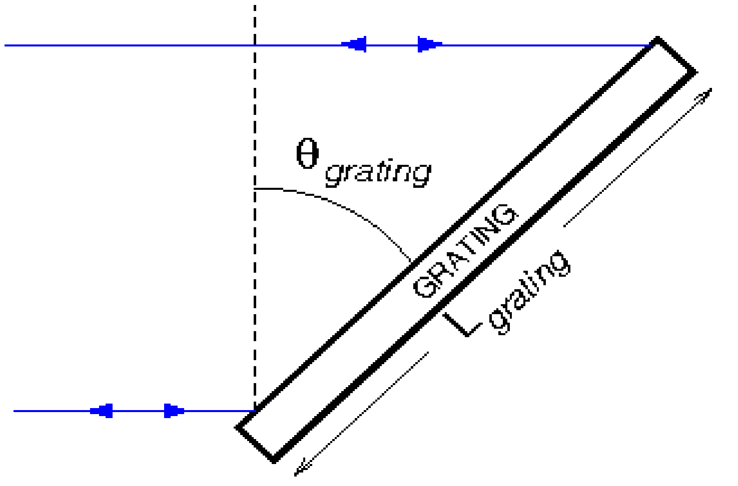
Angular dispersion: $D\beta/d\lambda = m/(d \cos \beta)$

So for high dispersion , choose high order and small line separation

Large gratings for large telescopes



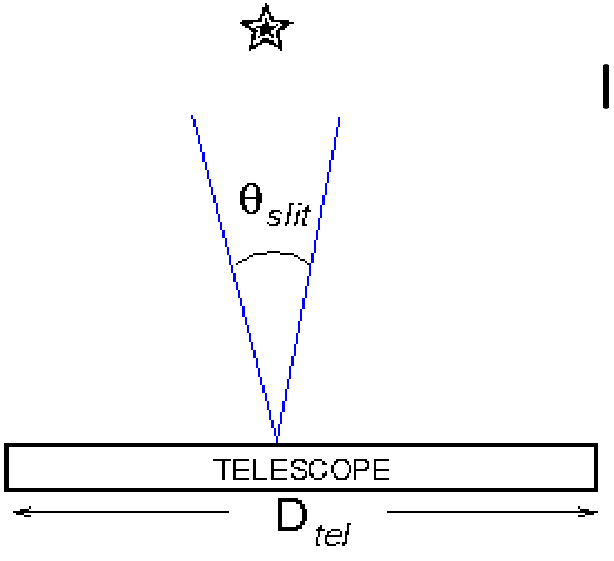
Reflection grating



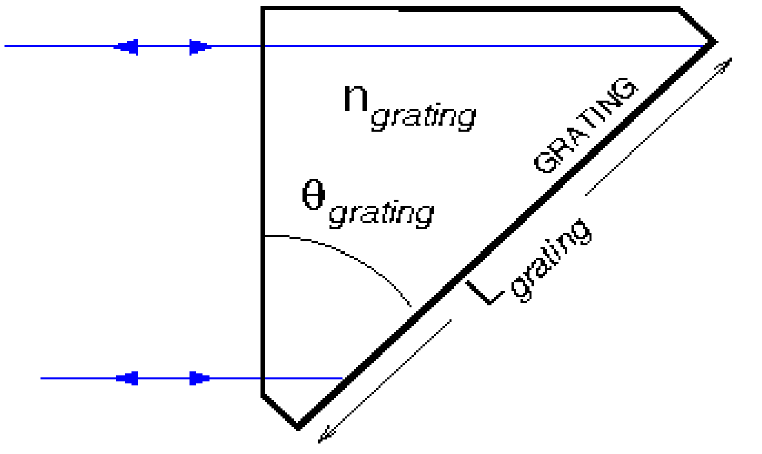
$$R = 10^4 \left(\frac{L_{grating}}{1.0 \text{ m}}\right) (\sin\theta_{grating}) \left(\frac{D_{tel}}{40 \text{ m}}\right)^{-1} \left(\frac{\theta_{slit}}{1"}\right)^{-1}$$

Different grating types, same size

Large gratings for large telescopes



Immersed reflection grating

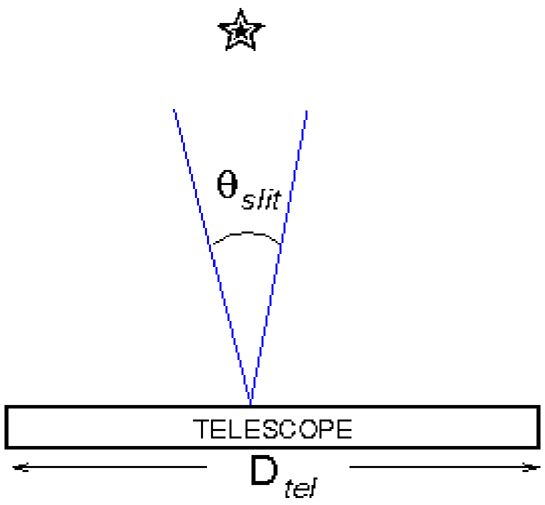


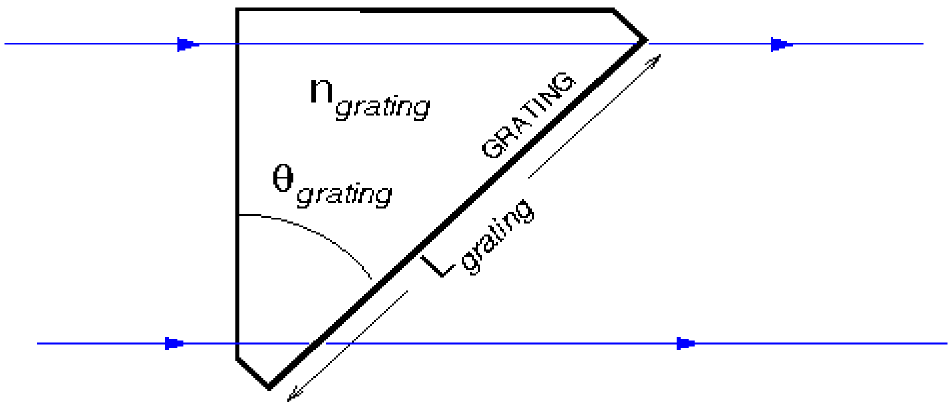
$$R = 10^4 \boxed{(n_{grating})} \left(\frac{L_{grating}}{1.0\ \mathrm{m}}\right) (\sin\theta_{grating}) \left(\frac{D_{tel}}{40\ \mathrm{m}}\right)^{-1} \left(\frac{\theta_{slit}}{1''}\right)^{-1}$$

May gain up to a factor of 3 (Si) or 4 (Ge), limits on size/uniformity

Large gratings for large telescopes

Grism (prism-grating, no deviation at blaze)





$$R = 10^4 \boxed{\left(\frac{n_{grating} - 1}{2}\right)} \left(\frac{L_{grating}}{1.0\ \mathrm{m}}\right) (\sin\theta_{grating}) \left(\frac{D_{tel}}{40\ \mathrm{m}}\right)^{-1} \left(\frac{\theta_{slit}}{1''}\right)^{-1}$$

No gain in size even using Ge (n=4)

Key Parameters

Spectral resolution

Grating length and overall size

Cost

Commercial Availability

Efficiency

Mass

Bandwidth

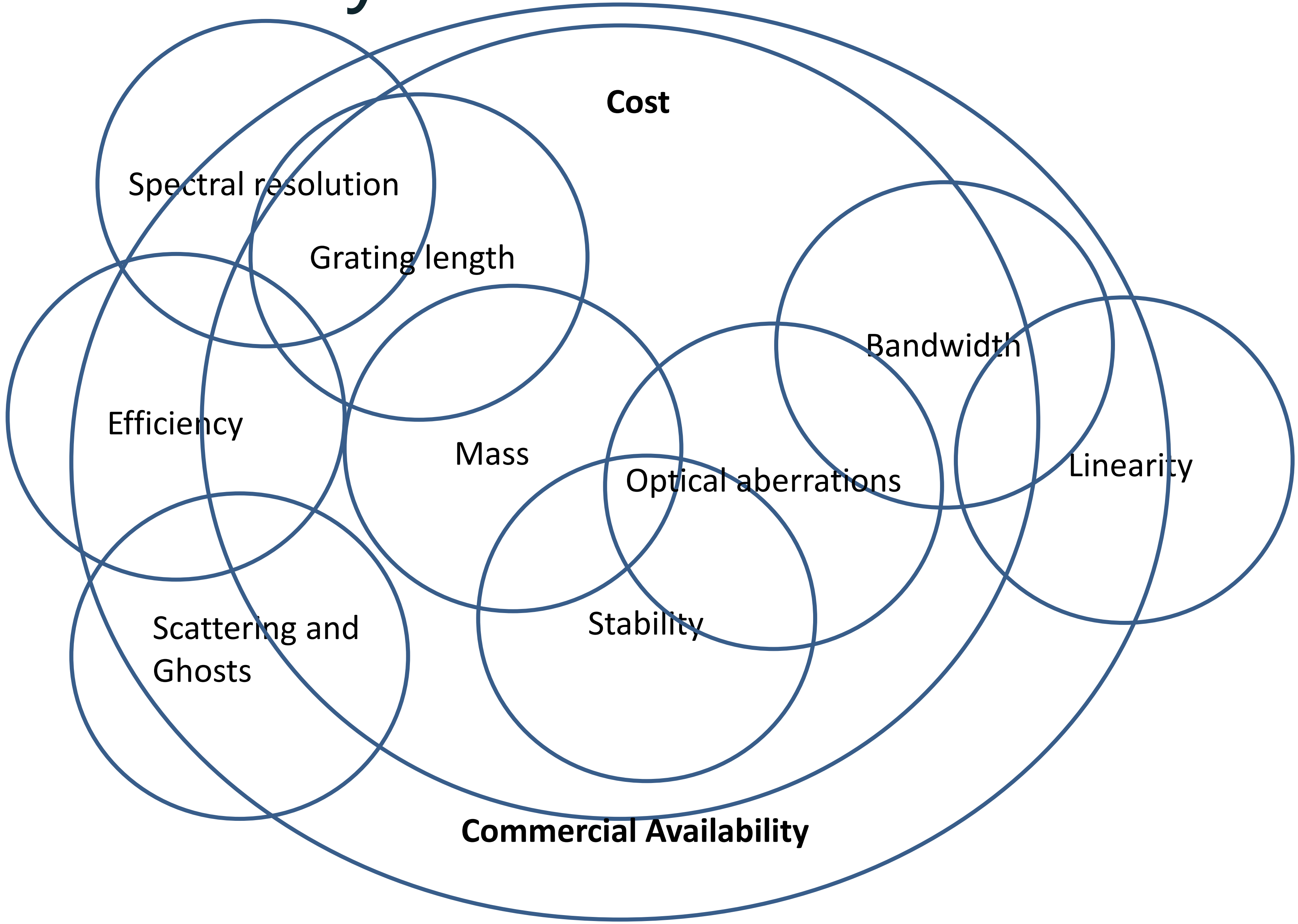
Linearity

Optical aberrations

Stability

Scattering and Ghosts

Key Parameters



This meeting will highlight means to reconcile these conflicting requirements

- Technology
  - Immersion Gratings
  - VPHG
  - Direct write VPG
  - Freeform gratings
  - AWGs
- Manufacturing Techniques
  - Silicon photolithography
  - Photo polymers
  - Holography
  - Diamond and ultraprecision machining
  - Ultrafast Laser inscription