Investigating the use of light diffraction for the closed-loop control of heliostats

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Overview

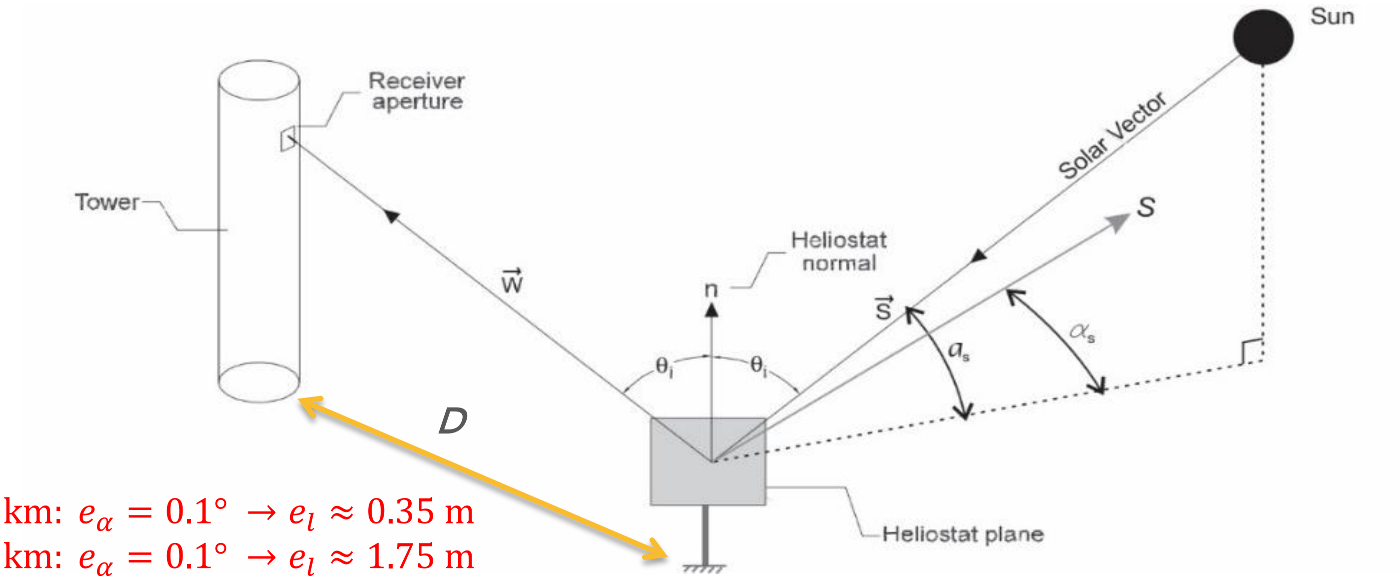
- Introduction
- Background
- Diffraction
- Method
- Conclusion

Introduction

- Heliostats in Central Receiver Systems

Introduction

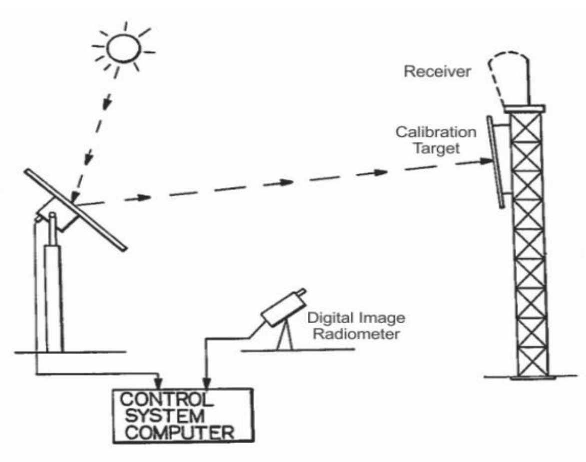
- Aiming Problem



$D = 0.2$ km: $e_\alpha = 0.1° \rightarrow e_l \approx 0.35$ m
$D = 1.0$ km: $e_\alpha = 0.1° \rightarrow e_l \approx 1.75$ m

Background

- Open-loop control

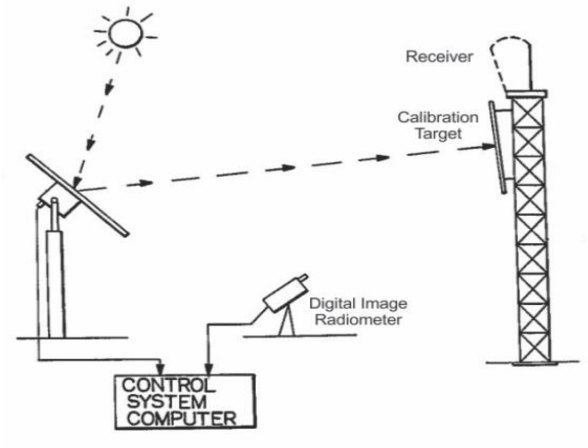


- Deterministic and non-deterministic error sources cause drift requiring calibration, which is time consuming

- No aiming feedback during operation requires drives with very tight tolerances which are costly

Background

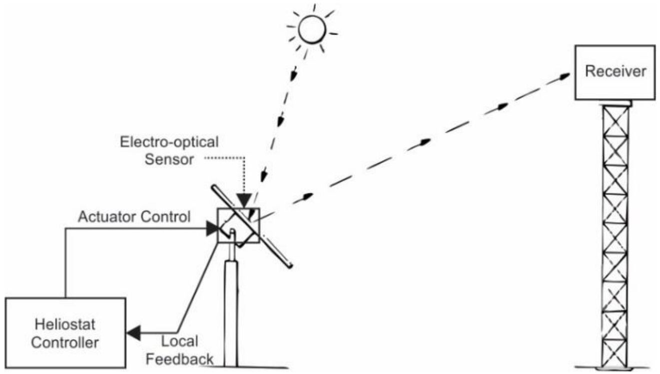
- Open-loop control



PS10 Gemosolar Coalinga Crescent D. Sierra ST.

Background

- Closed-loop (local feedback)

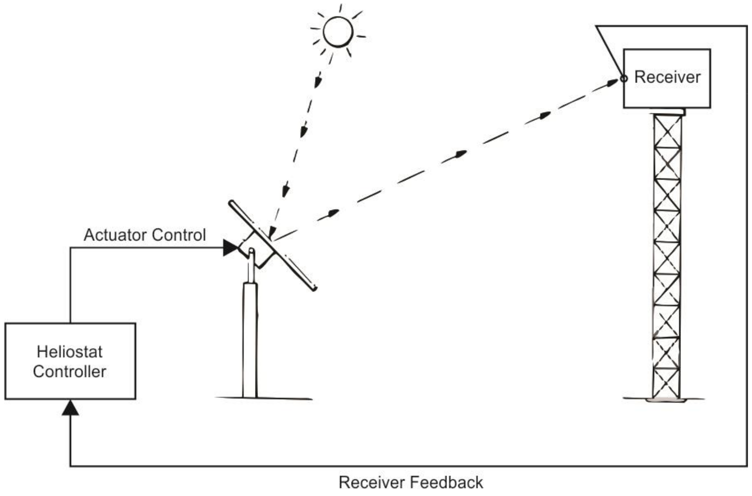


- Real-time alignment feedback negates the need for expensive drives with tight tolerances

- Mounting sensors on every heliostat can be expensive, esp. for large helio. fields

Background

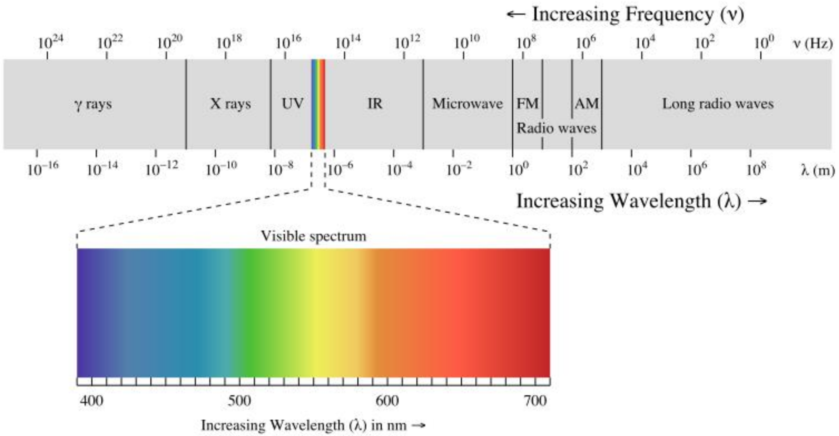
- Closed-loop ("Receiver" feedback)



- Real-time alignment feedback negates the need for expensive drives with tight tolerances
- Does not require sensors on every heliostat
- Multiple/All heliostats can be controlled simultaneously

Diffraction

- Electromagnetic Spectrum



Diffraction

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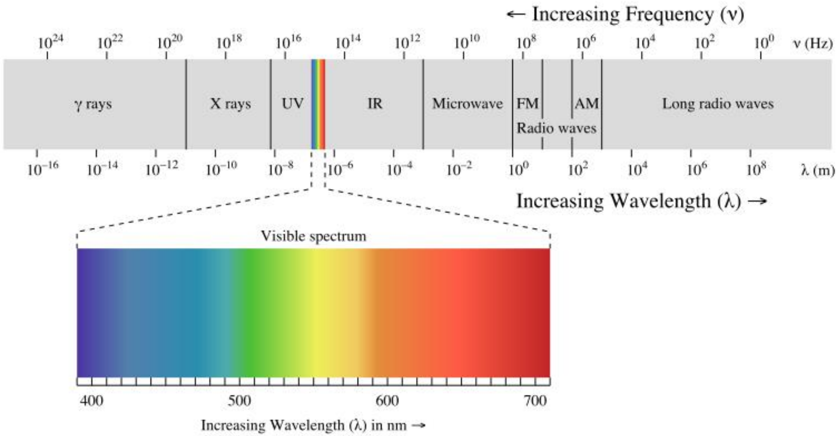
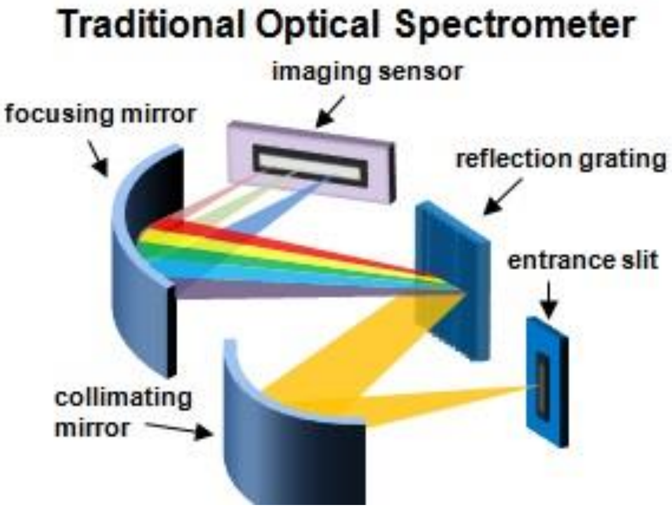
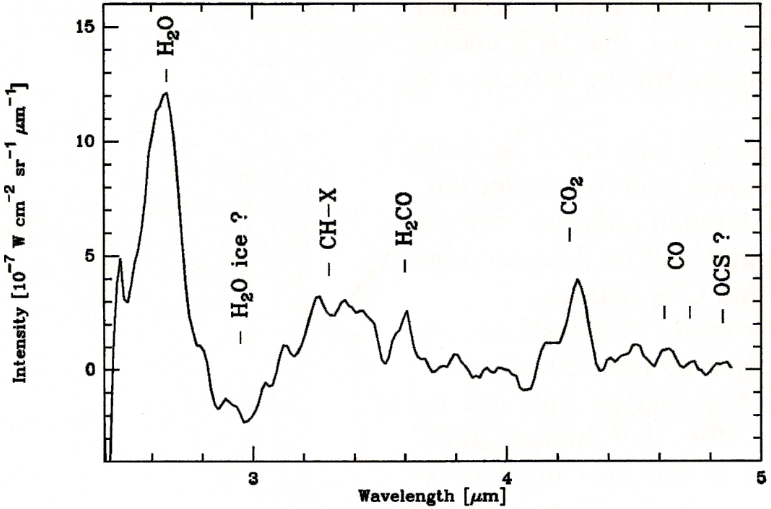


Diffraction

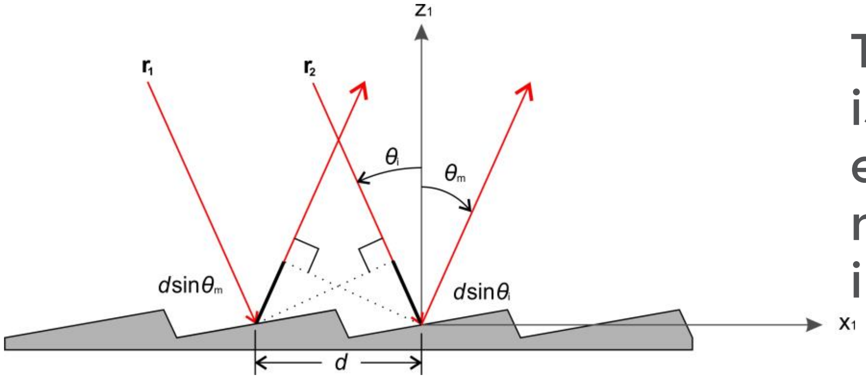
- Spectroscopy





Diffraction

- Diffraction gratings: Interference



The path difference between r_1 and r_2 is $d\sin\theta_m + d\sin\theta_i$. If this difference is equal to the wavelength λ (or a multiple, $\mathrm{m}\lambda$, thereof), $r_1$and r_2 will interfere constructively:

$$d\sin\theta_m + d\sin\theta_i = \mathrm{m}\lambda \qquad m = 0, \pm 1, \pm 2 \ldots$$

$$\theta_m(\lambda) = \sin^{-1}\left(\frac{\mathrm{m}\lambda}{d} - \sin\theta_i\right)$$

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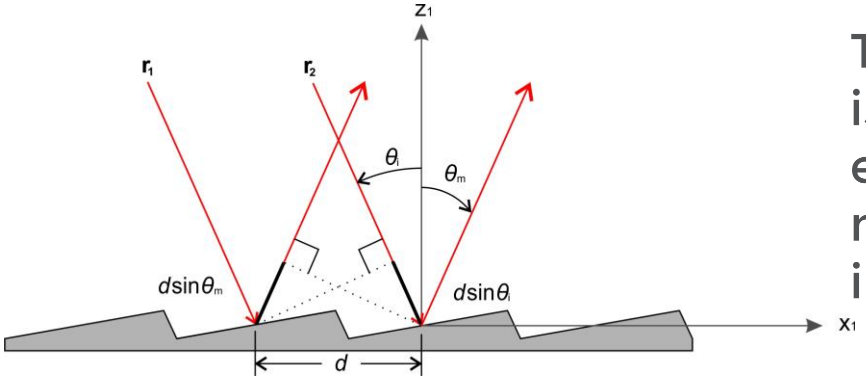

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	m=0	m=1	m=2
θ_m(473 nm)	0°	13.7°	28.2°

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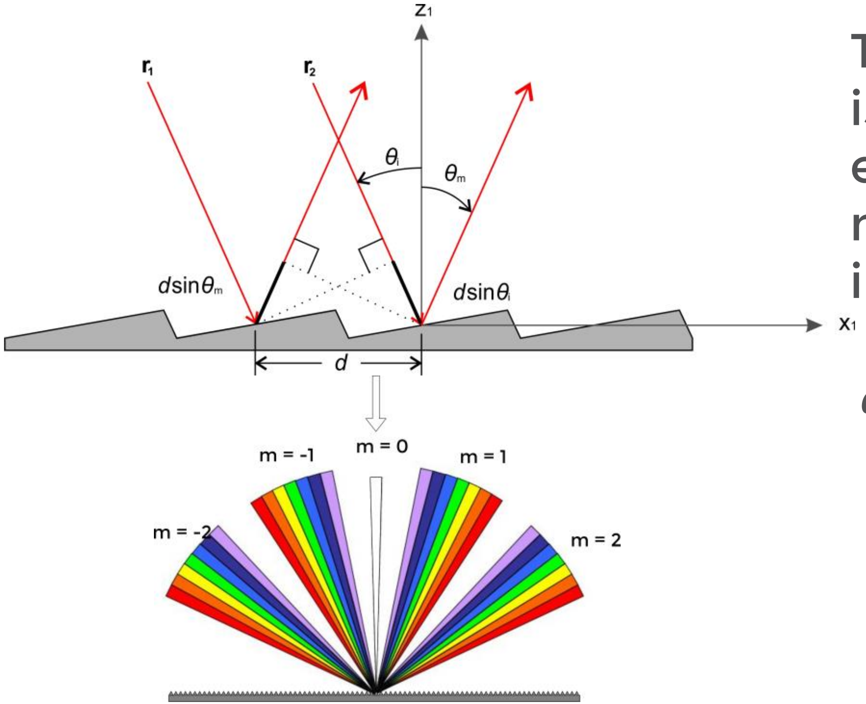

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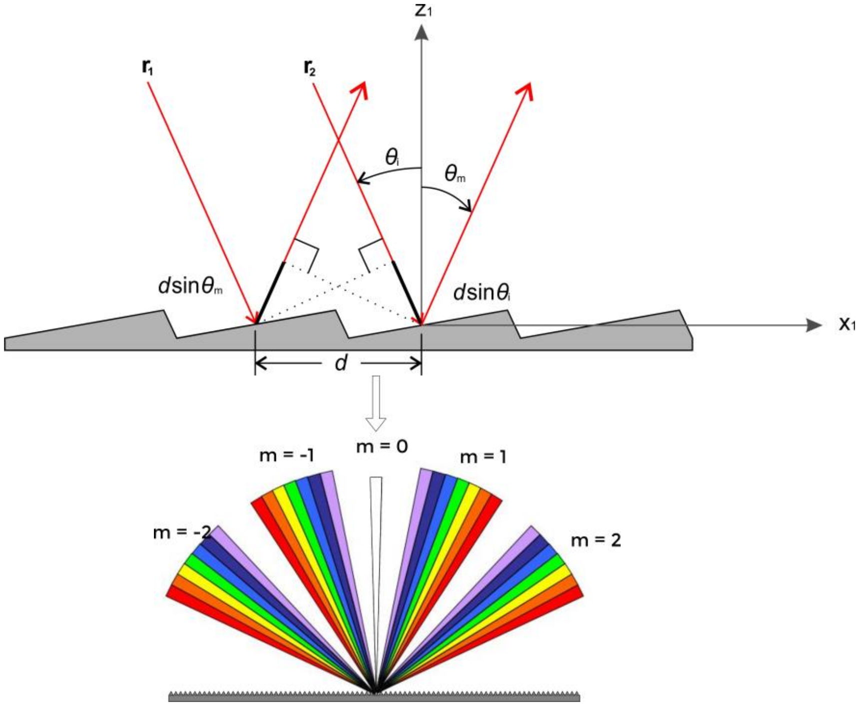

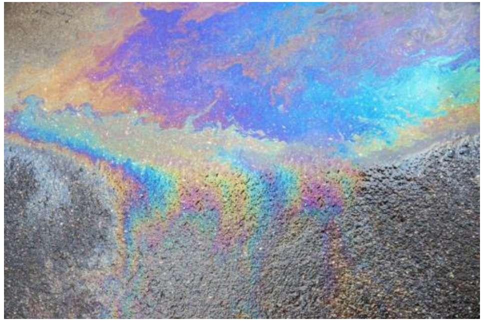

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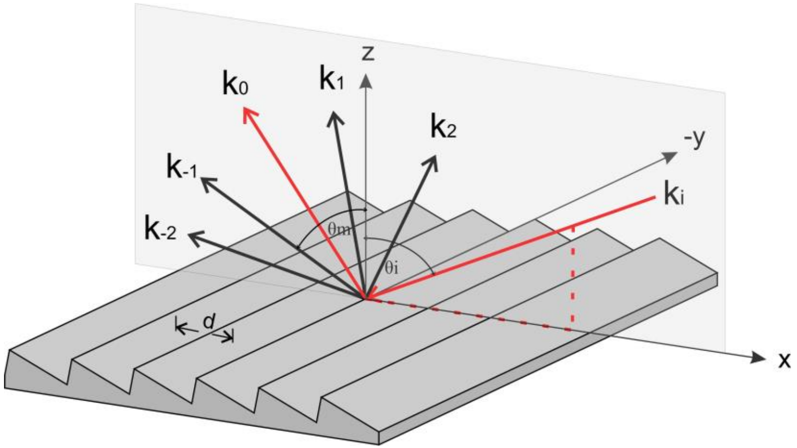
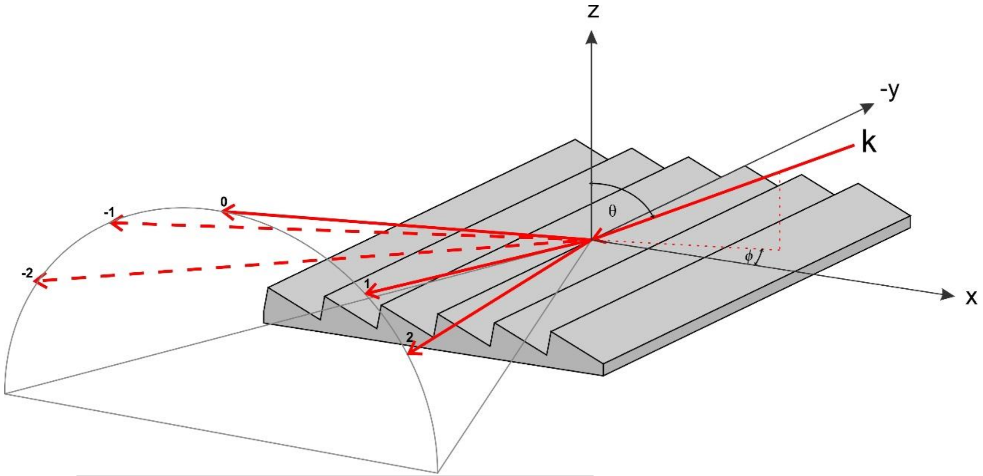
Diffraction

- 1-D (Linear) diffraction grating



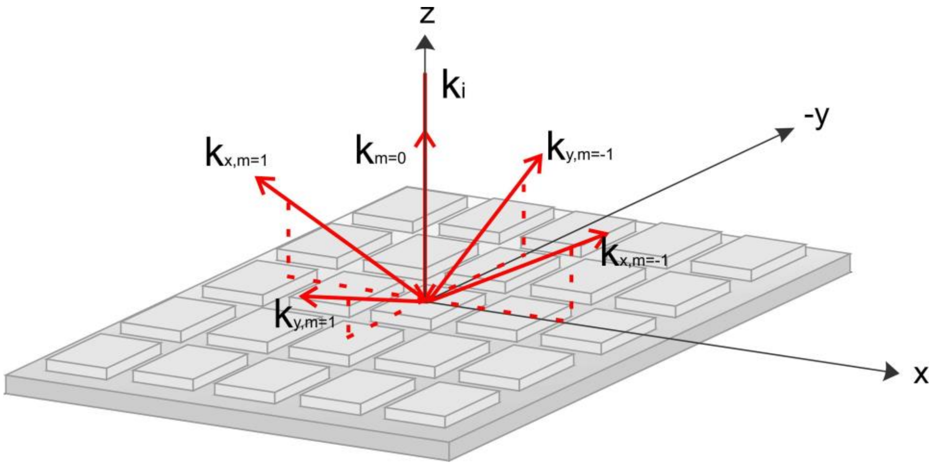


$$\sin\theta_m = \sin\theta_i + m\frac{\lambda}{d}$$

$$\cos\phi_i\,(\sin\theta_m - \sin\theta_i) = \frac{m\lambda}{d}$$
$$d(\sin\phi_m - \sin\phi_i) = 0$$

Diffraction

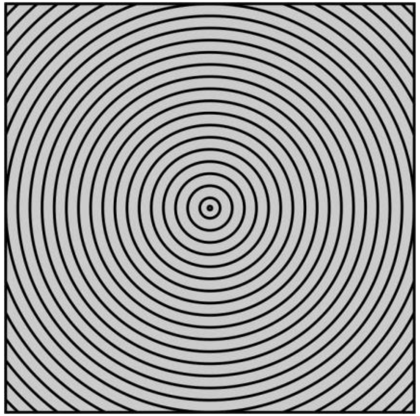
- Crossed (2-D) diffraction gratings



Diffraction orders will propagate in two directions, but the vector sum of the surface components of the diffraction orders in each direction represent another propagation direction.

Diffraction

- Circular diffraction grating



Diffraction

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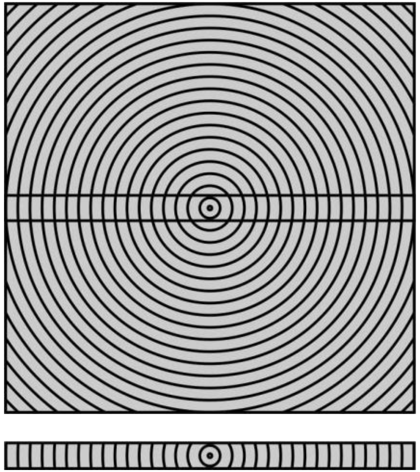

Diffraction

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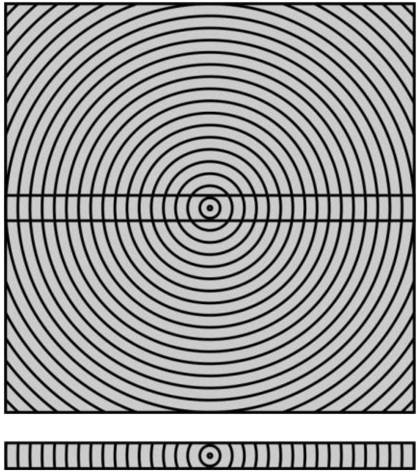

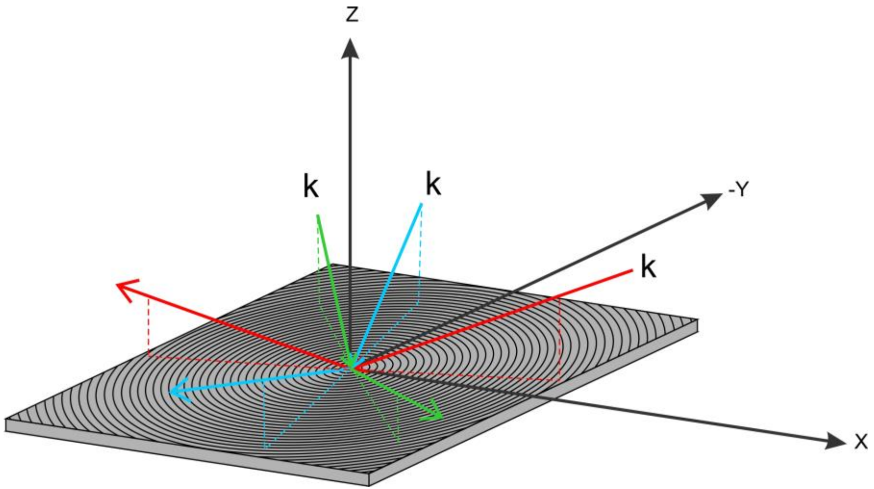

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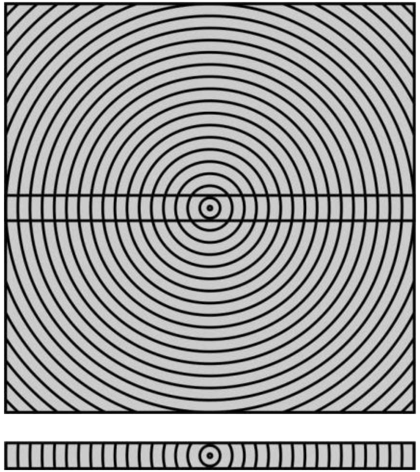

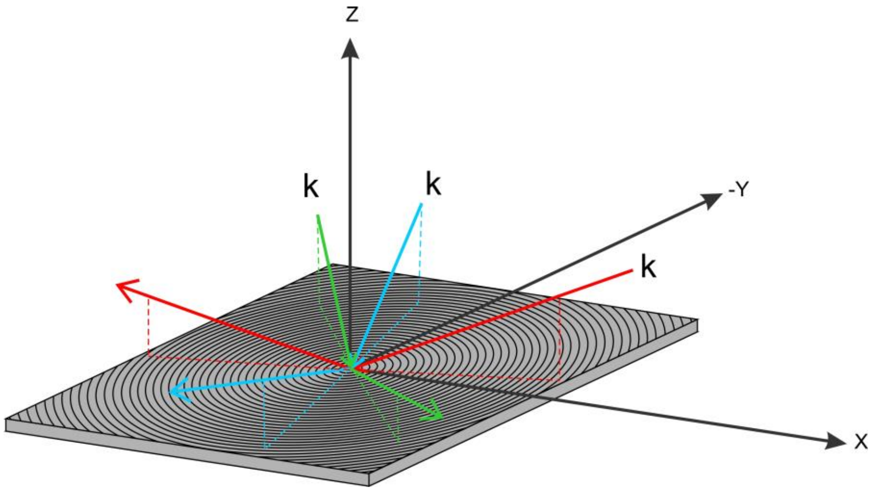

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Diffraction

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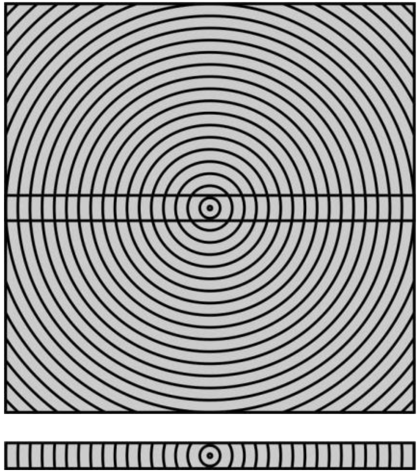

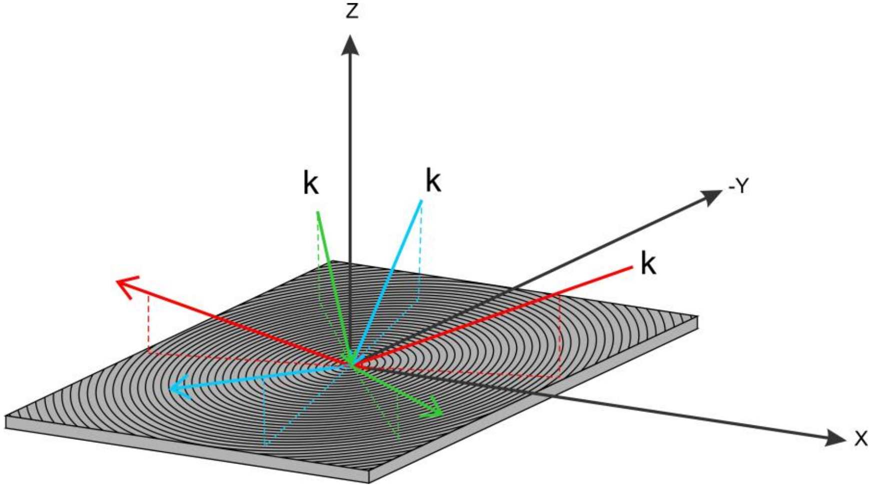

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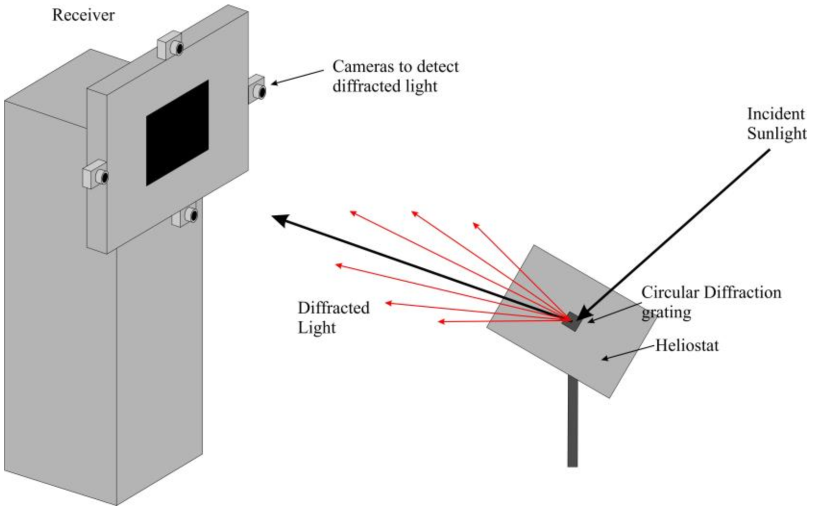
Method

- Overview

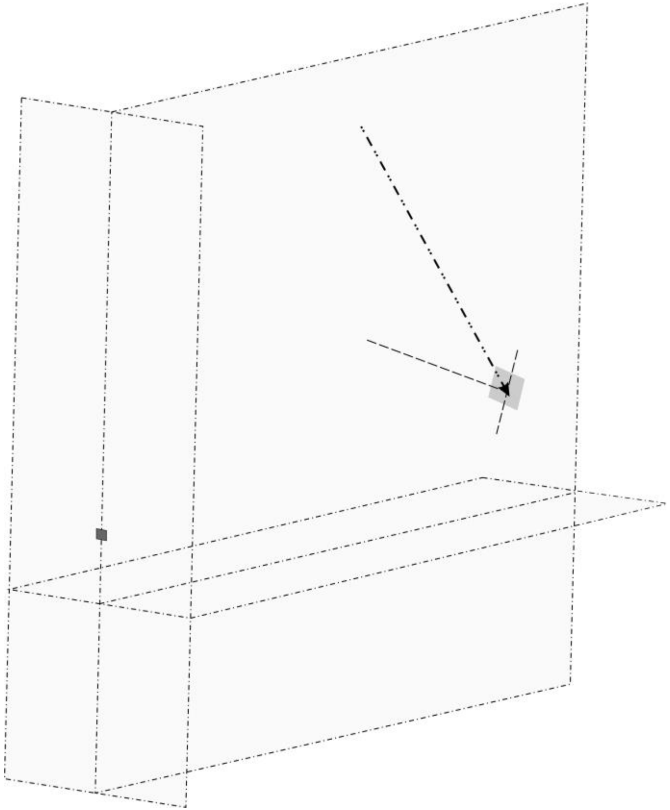


- Aim: Determine direction of the zeroth propagation order (direction of the zeroth propagation order coincides with the reflected beam).
- Camera senses the colour of diffracted light from some propagation order (1^{st}), infers wavelength
- The light diffracted in the direction of the camera has a functional relationship with the zeroth order.

Method

- Determining $k_{m=0}$: One camera viewpoint

  - 1 Camera observes diffracted light and observes a specific colour, inferring the wavelength
  - Since the circular diffraction grating diffracts light into a cone, there are an infinite directions for the zeroth order reflected beam, but is constrained to lie on a surface of a cone with vertex angle 2θ and with axis along the camera-grating vector
  - Set of all possible incident vectors is the reflection (Snell's law) of the set of all possible reflection vectors and therefore also lies in a cone with angle vertex 2θ. Its axis is the reflection of the camera-grating vector.



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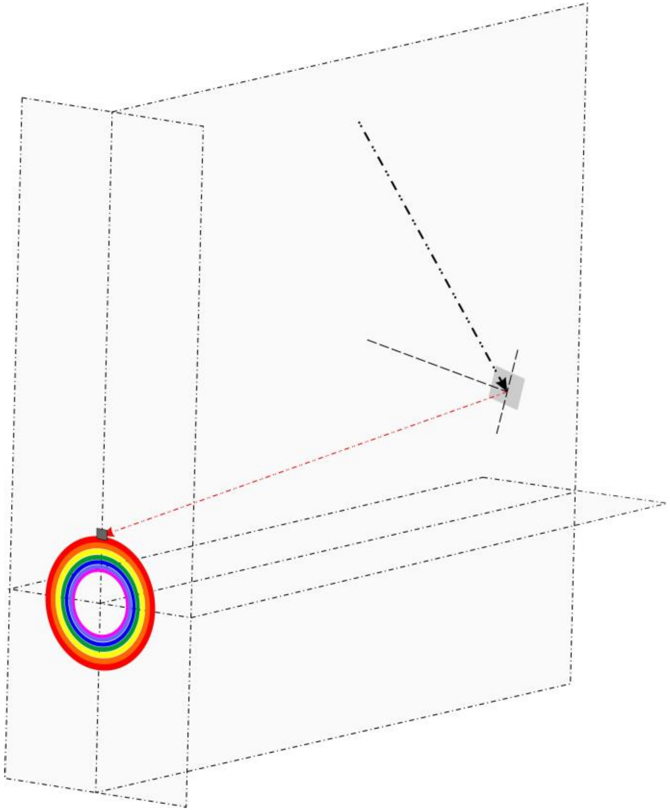

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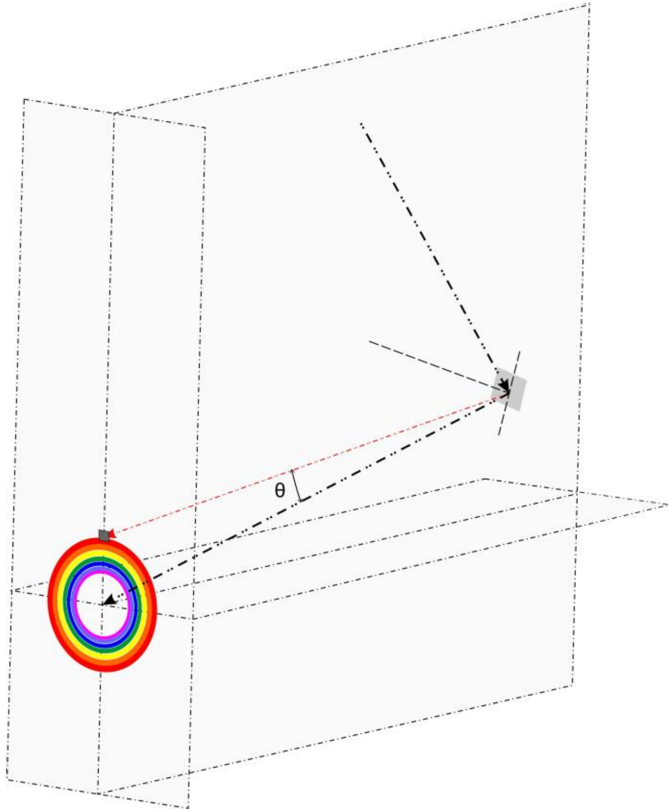

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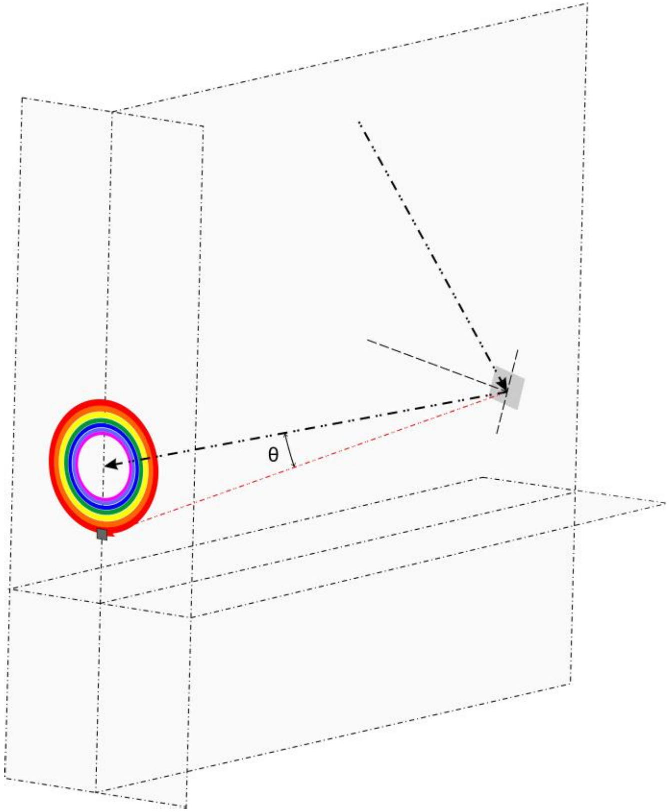

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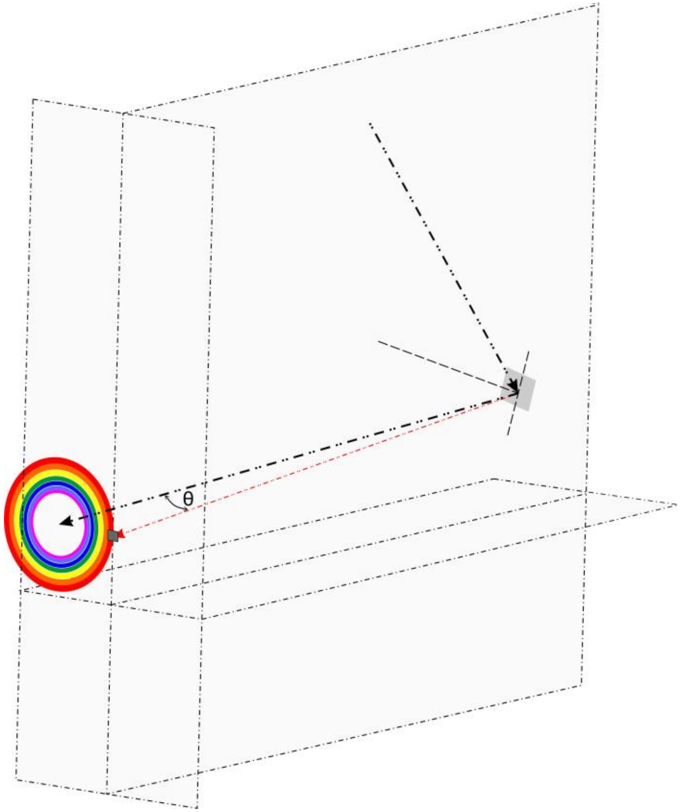

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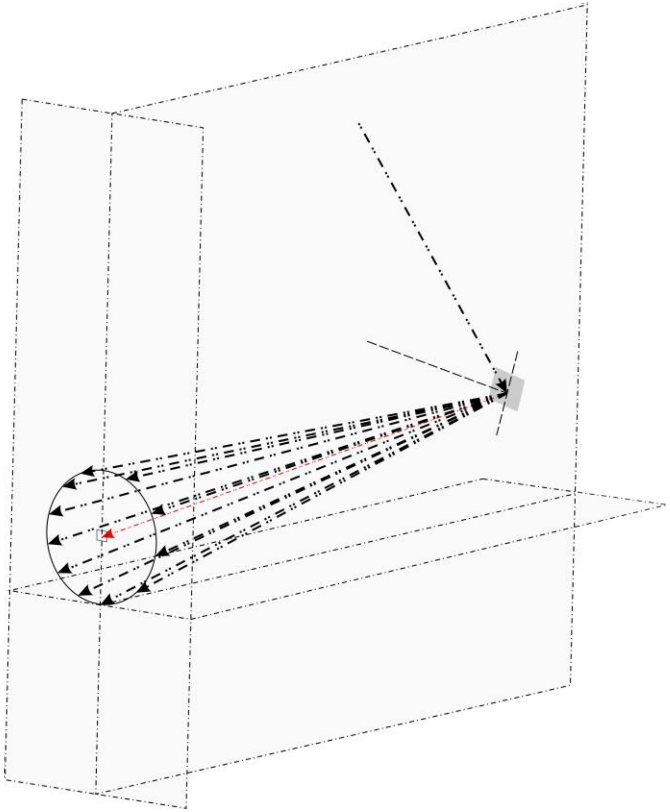
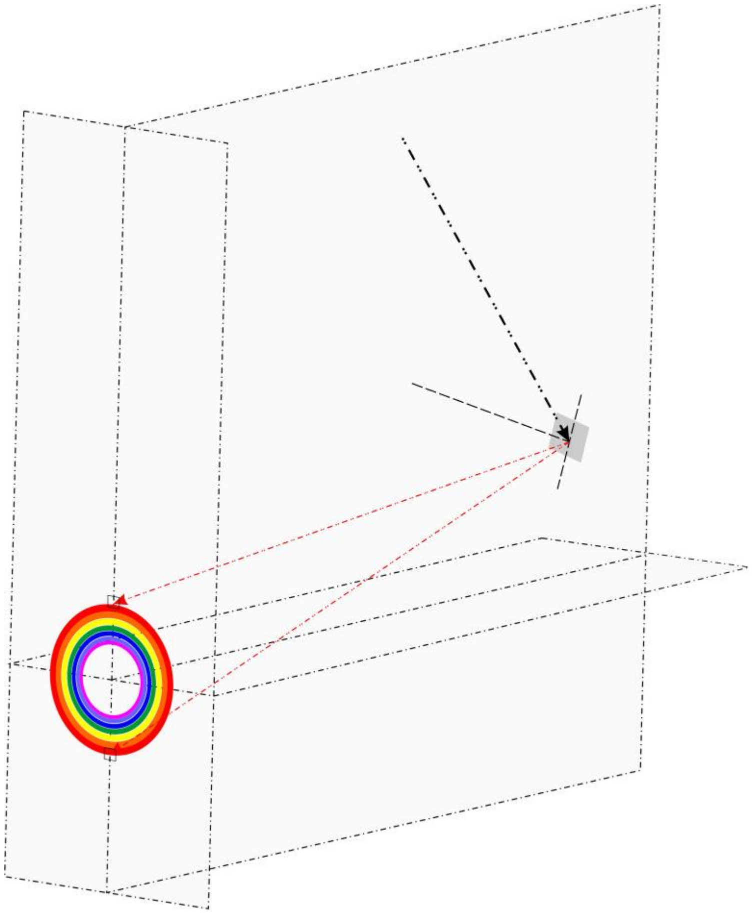


Method

- Determining $k_{m=0}$:
  Two camera viewpoints



Special case: Incident light, grating normal and cameras lie in a plane.

- 2 Camera each observes diffracted light and each observes a specific colour, each inferring the wavelength.

- For each viewpoint, there are an infinite number of directions for the zeroth order reflected beam, but is constrained to lie on a surface of a cone

- The intersection of the bases of the cones is the unique solution for the direction of the zeroth order

Method

- Determining $k_{m=0}$:
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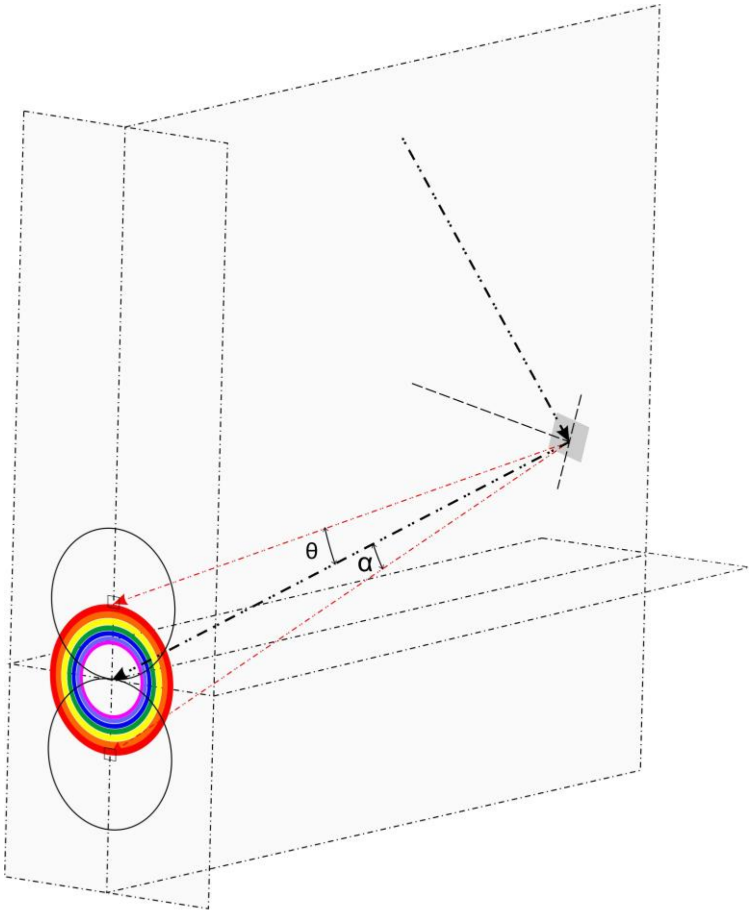


Method

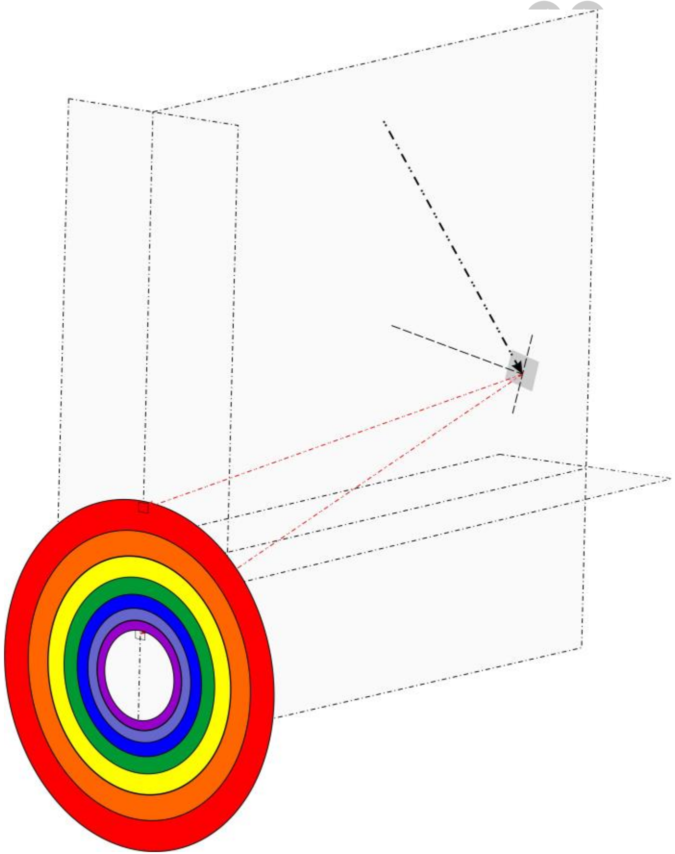
- Determining $k_{m=0}$:
  Two camera viewpoints

Similar special case: Incident light, grating normal and cameras lie in a plane.

- Set of possible reflection vectors for one viewpoint is encircled by the set of possible reflection vectors for the other viewpoint

- Again, the intersection of the bases of the cones is the unique solution for the direction of the zeroth order

- Can be shown that the intersection of the two circles is the unique solution for the direction of the zeroth order of the incident ray lies in the plane



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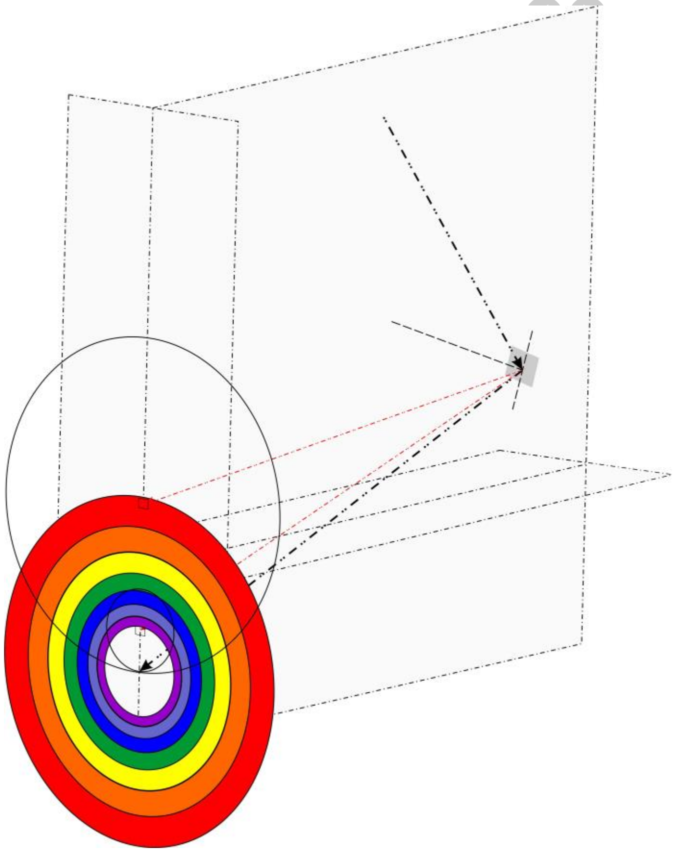


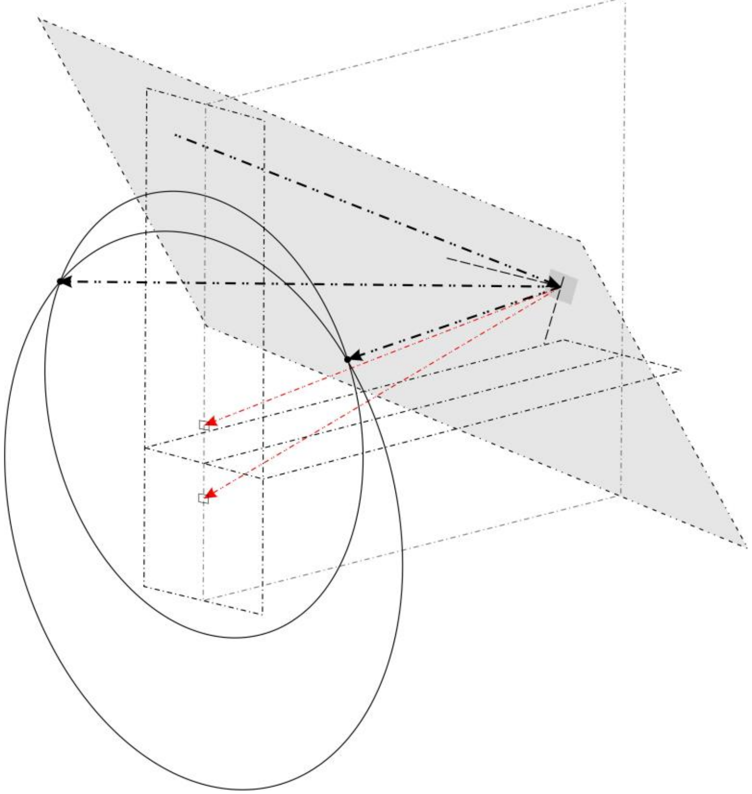
Method

- Determining $k_{m=0}$: Two camera viewpoints

General case: Incident light lies in a an arbitrary plane

- The set of possible reflection vectors again lie along the surface of a cone for each viewpoint, but in this case there are two intersections.

- Therefore there is not a unique solution for the direction of the zeroth order vector

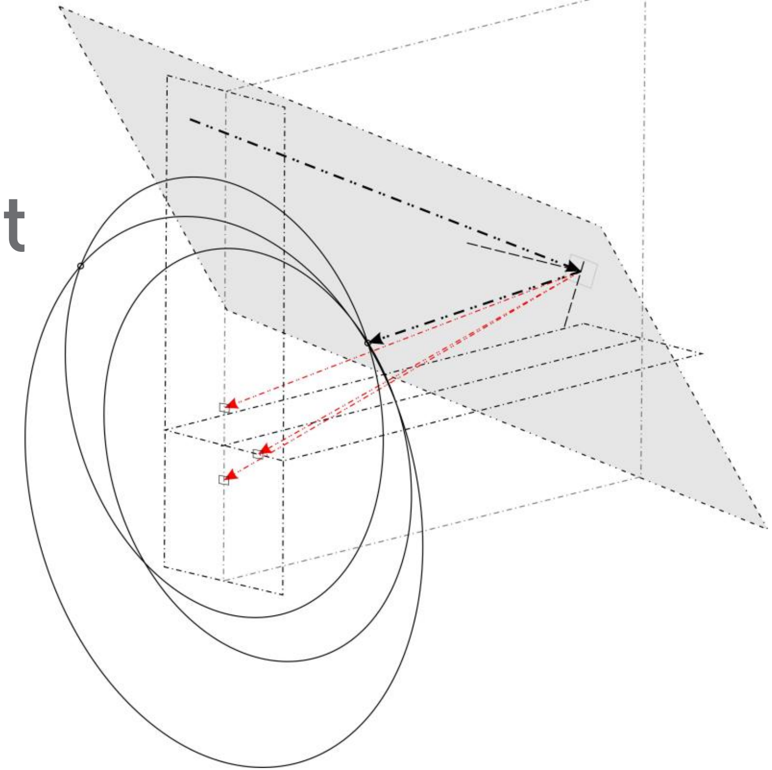


Method

- Determining $k_{m=0}$:
  Three camera viewpoint

General case: Incident light lies in a an arbitrary plane

- Adding a third camera viewpoint will provide a unique solution



Conclusion

- Design of diffraction grating
  - Propagation directions independent of grating profile
  - Profile determines the power diffracted into each order (blazing)
- Ray-trace simulation
- Experimentation

Thank You

ACKNOWLEDGEMENTS:

Dr W.J. Smit

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