SIGGRAPH 99 Course on
3D Photography

Acquiring Images

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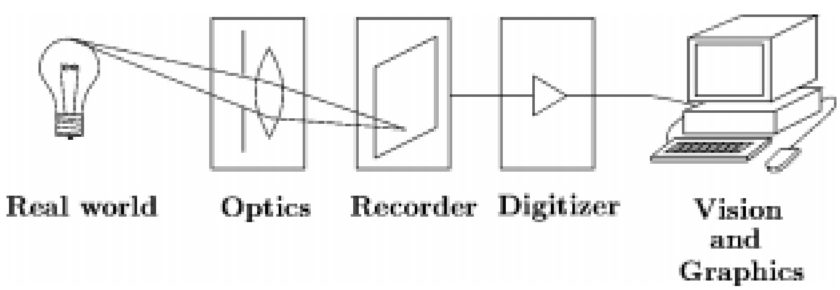
The Imaging Pipeline



Overview

Pinhole camera

Lenses

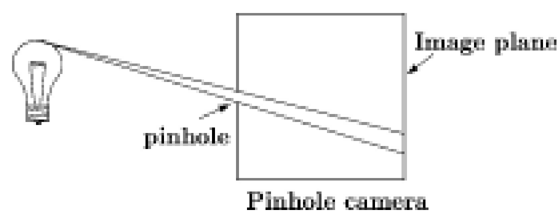
- Principles of operation
- Limitations

Charge-coupled devices

- Principles of operation
- Limitations

The pinhole camera

The first camera - “camera obscura” - known to Aristotle.

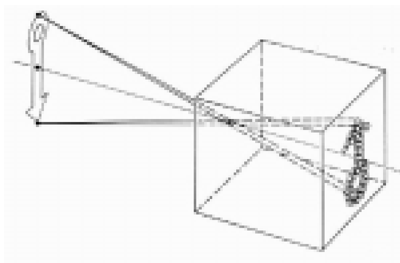


Small aperture = high fidelity

***but* requires long exposure or bright illumination**

Pinhole camera

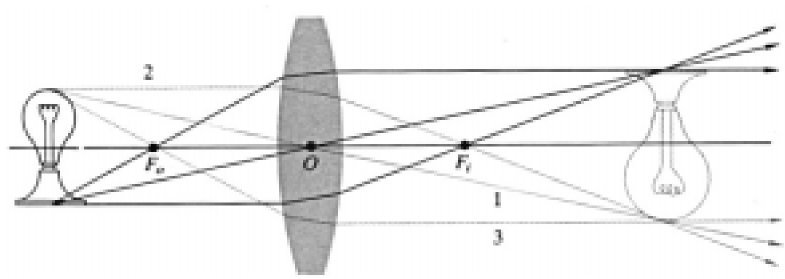
If aperture is too small, then diffraction causes blur.



[Figure from Hecht87]

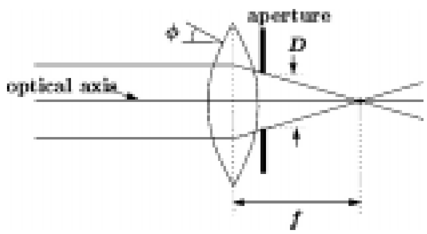
Lenses

Lenses focus a bundle of rays to one point.
=> can have larger aperture.



[Figure from Hecht87]

Lenses



A lens images a bundle of parallel rays to a focal point at a distance, *f*, beyond the plane of the lens.

Note: *f* is a function of the index of refraction of the lens.

An aperture of diameter, *D*, restricts the extent of the bundle of refracted rays.

Lenses

For economical manufacture, lens surfaces are usually spherical.

A spherical lens is behaves ideally if *Φ* is small:

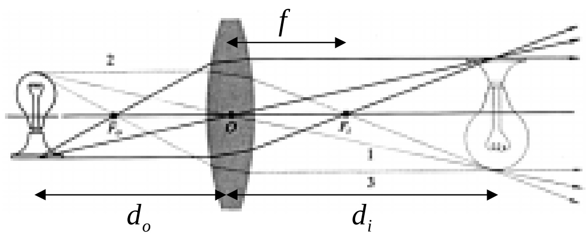
$$\sin\phi = \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \ldots \approx \phi$$

The angle restriction means we consider rays near the optical axis -- "paraxial rays."

Lenses

For a "thin" lens, we ignore lens thickness, and the paraxial approximation leads to the familiar Gaussian lens formula:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$



[Figure from Hecht87]

Cardinal points of a lens system

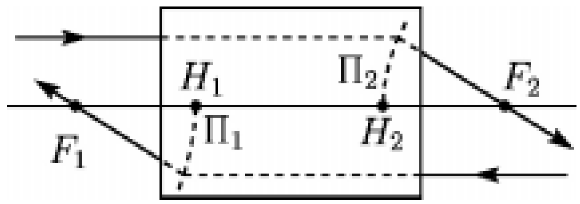
Most cameras do not consist of a single thin lens.

Rather, they contain multiple lenses, some thick.

A system of lenses can be treated as a "black box" characterized by its *cardinal points*.

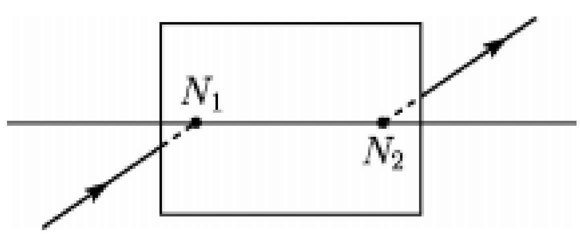
Focal and principal points

The focal and principal points and the principal "planes" describe the paths of rays parallel to the optical axis.



Nodal points

The nodal points describe the paths of rays that are not refracted, but are translated down the optical axis.



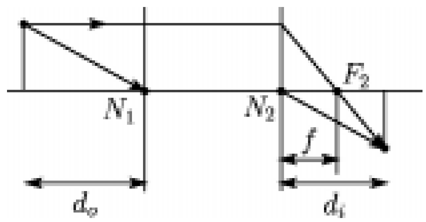
Cardinal points of a lens system

If:

- ***the optical system is surrounded by air***
- ***and the principal planes are assumed planar***

then

- ***the nodal and principal points are the same***



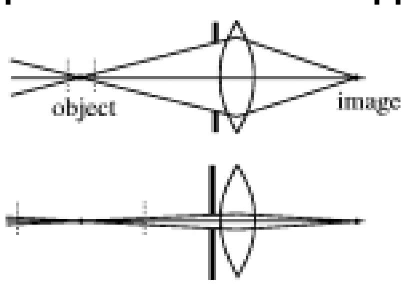
The system still obeys Gauss's law, but all distances are now relative to the principal points.

Depth of field

Lens systems do have some limitations.

First, points that are not in the object plane will appear out of focus.

The *depth of field* is a measure of how far from the object plane points can be before appearing "too blurry."



Monochromatic aberrations

Allowing for the next higher terms in the sin*Φ* approximation:

$$\sin\phi = \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} - ... \approx \phi - \frac{\phi^3}{3!}$$

…we arrive at the third order theory. Deviations from ideal optics are called the *primary* or *Seidel aberrations*:

- **Spherical aberration**
- **Coma**
- **Astigmatism**
- **Petzval curvature**
- **Distortion**

Distortion

Cause:

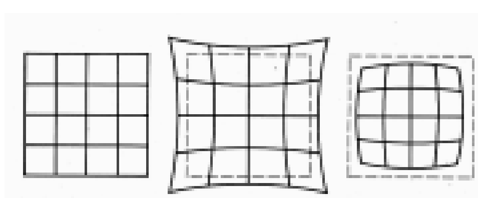
Oblique rays bent by the edges of the lens

Effect:

Non-radial lines curve out (barrel) or curve in (pin cushion)

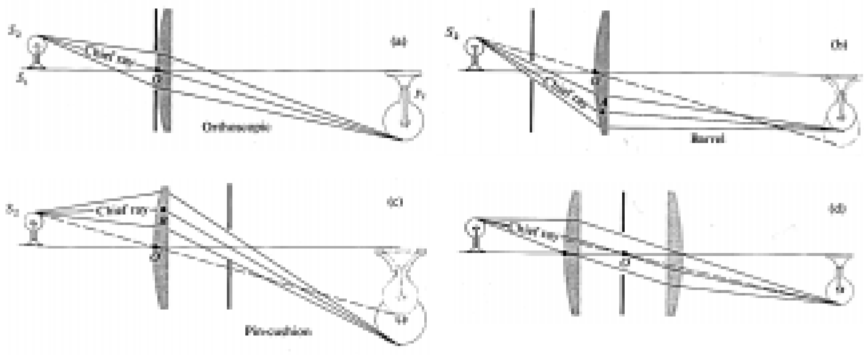
Ways of improving:

Symmetrical design.



[Figure from Hecht87]

Distortion



[Figures from Hecht87]

Chromatic aberration

Cause:

Index of refraction varies with wavelength.

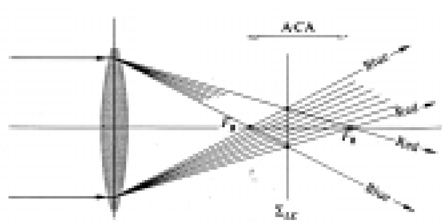
Effect:

Focus shifts with color, colored fringes on highlights

Ways of improving:

Achromatic designs

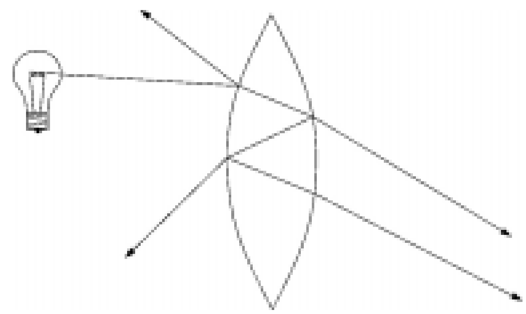
[Figure from Hecht87]



Flare

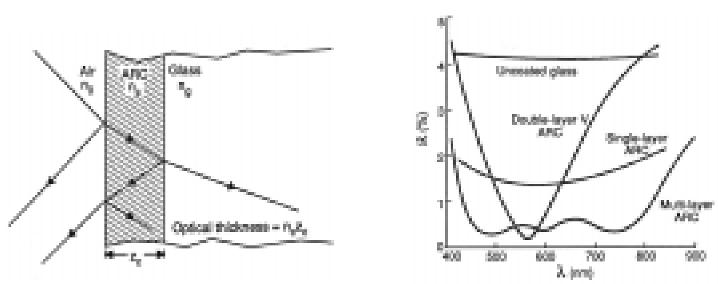
Light rays refract *and reflect* at the interfaces between air and the lens.

The "stray" light is not focused at the desired point in the image, resulting in ghosts or haziness.



Optical coatings

Optical coatings are tuned to cancel out reflections at certain angles and wavelengths.



[Figure from Burke96]

Vignetting

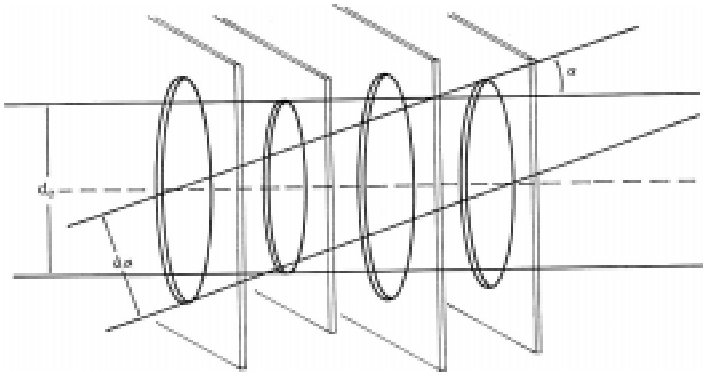
Light rays oblique to the lens will deliver less power per unit area (irradiance) due to:

- **mechanical vignetting**
- **optical vignetting**

Result: darkening at the edges of the image.

Mechanical vignetting

Occlusion by apertures and lens extents results in mechanical vignetting.



[Figure from Horn87]

Optical vignetting

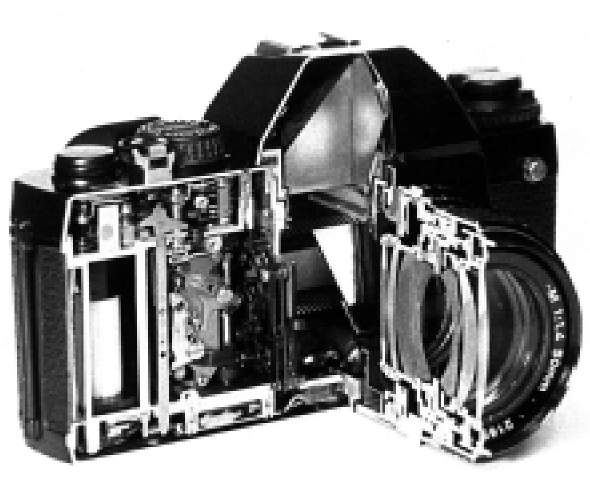
At grazing angles, less power per unit area is delivered to the image plane -- optical vignetting.

The irradiance at the sensor varies with the angle to the image plane, $\boldsymbol{\theta}$, as:

$$E \sim L\left(\frac{D}{f}\right)^2 \cos^4\theta$$

Note also: the irradiance is proportional to the radiance along the path.

The art of optical design...



[Figure from Goldberg92]

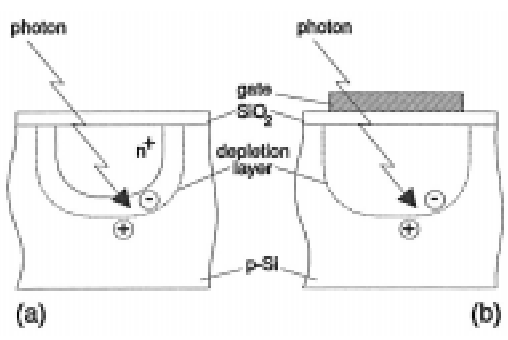
Charge-coupled devices

The most popular image recording technology for 3D photography is the charge-coupled device (CCD).

- ***Image is readily digitized***
- ***CCD cells respond linearly to irradiance***
  - *But, camera makers often re-map the values to correct for TV monitor gamma or to behave like film*
- ***Available at low cost***

Photo-conversion

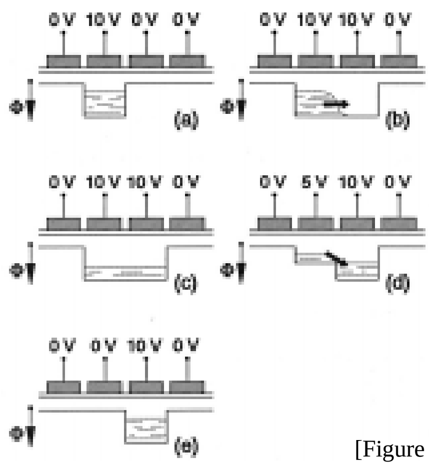
When a MOS capacitor is biased into "deep depletion," it can collect charges generated by photons.



[Figure from Theuwissen87]

Charge transfer

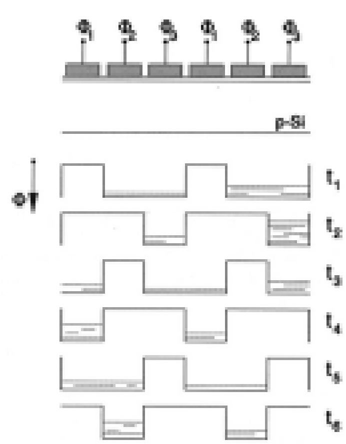
By manipulating voltages of neighboring cells, we can move a bucket of charge one gate to the right.



[Figure from Theuwissen87]

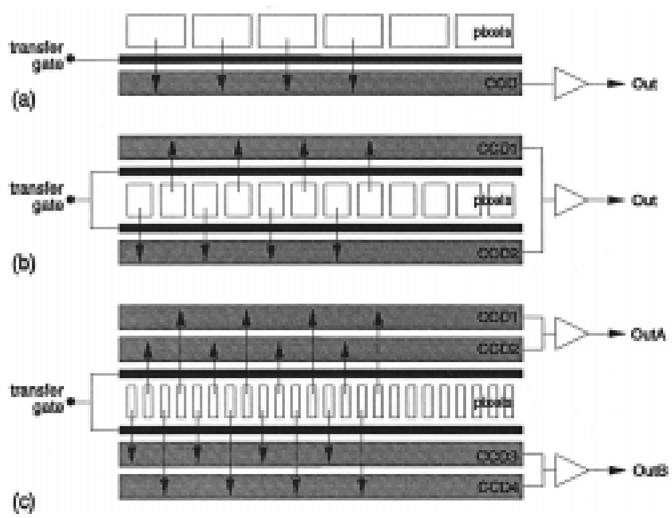
Three-phase clocking system

With three gates, we can move disjoint charge packets along a linear array of CCD's.



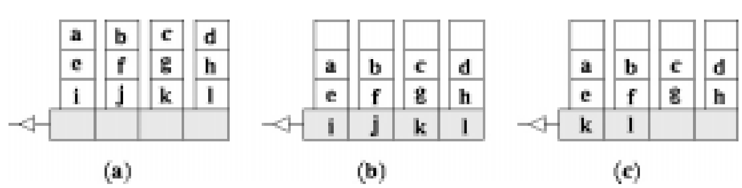
[Figure from Theuwissen87]

Linear array sensors

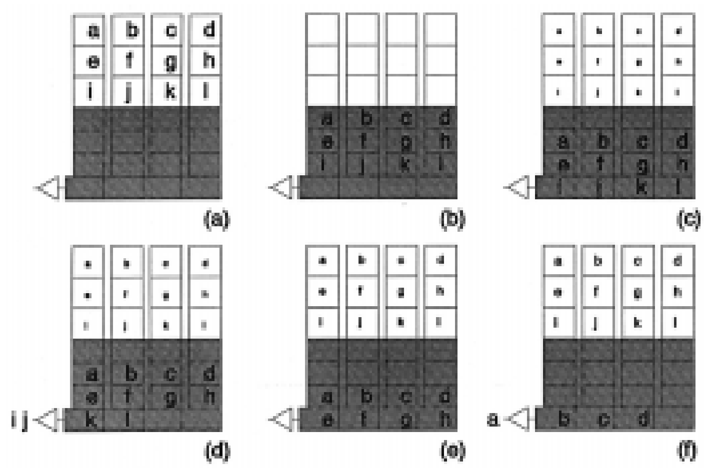


[Figure from Theuwissen87]

Full frame CCD

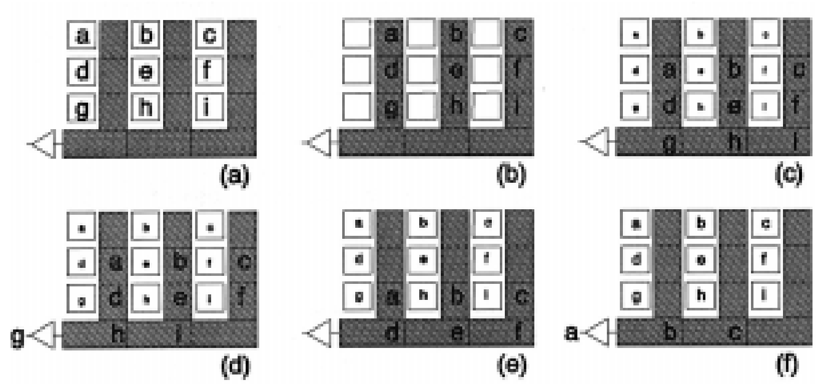


Frame transfer (FT) CCD



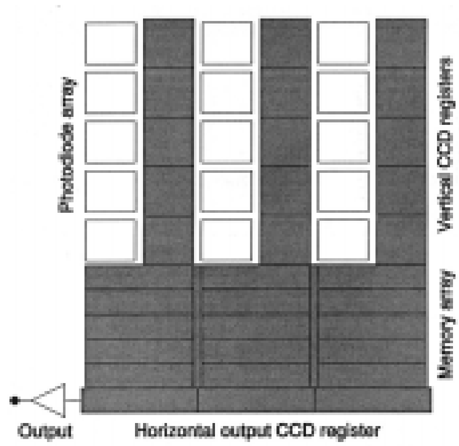
[Figure from Theuwissen87]

Interline transfer (IT) CCD



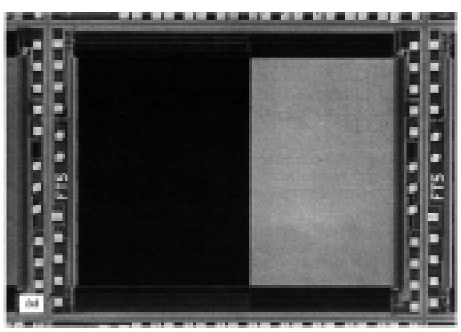
[Figure from Theuwissen87]

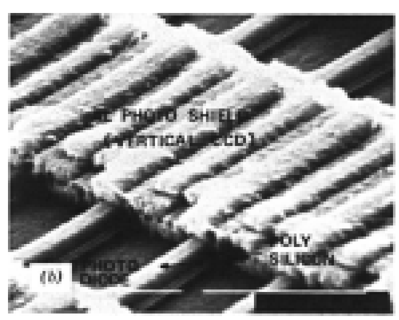
Frame interline transfer (FIT) CCD’s



[Figure from Theuwissen87]

A closer look...



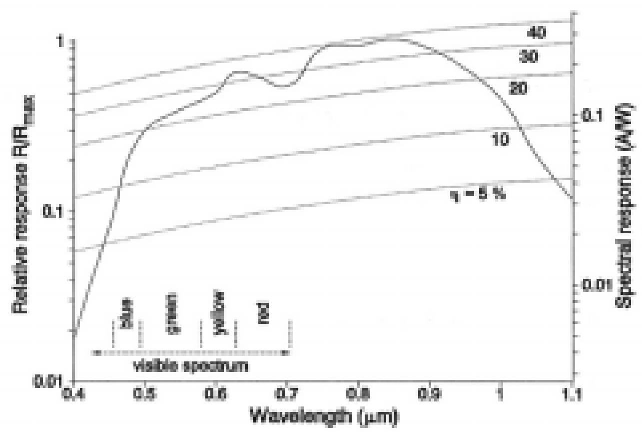


Frame transfer

Interline transfer

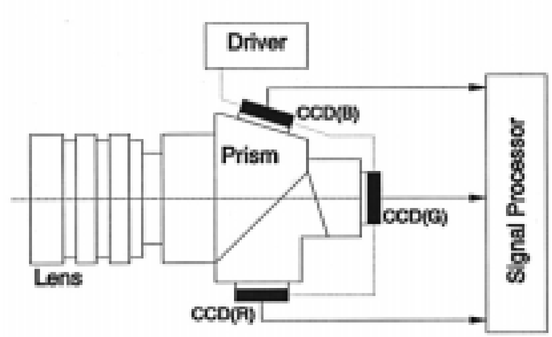
[Figure from Muller86]

Spectral response



[Figure from Theuwissen87]

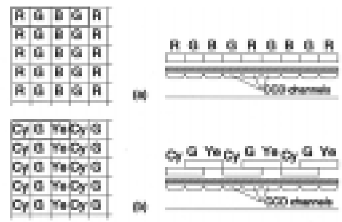
3-chip color cameras

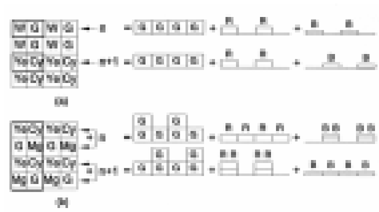


[Figure from Theuwissen87]

Single chip color filters

Stripe filters





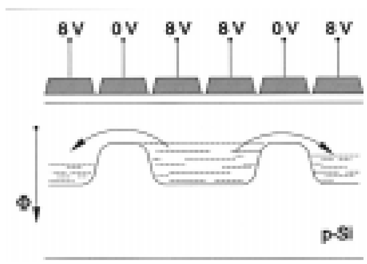
Mosaic filters

[Figures from Theuwissen87]

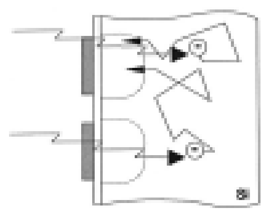
Limitations of CCD’s

- **Smear vs. aliasing**
- **Blooming**
- **Diffusion**
- **Transfer efficiency**
- **Noise**
  - ***Processing defects***
  - ***Dark-current noise***
  - ***Output amplifier noise***
- **Dynamic range**

Blooming and diffusion



Blooming



Diffusion

[Figures from Theuwissen87]

Bibliography

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