Secondary Spectrum

Lens Design OPTI 517
The quadratic difference between the F and C wavefronts is:

\[ \delta_\lambda W_{020} = \frac{1}{2} \sum \frac{y_m^2}{f \nu} \]

V-number
\[ \nu = \frac{n_d - 1}{n_F - n_C} \]

\[ \delta_\lambda W_{020} = \frac{1}{2} \sum \frac{y_m^2}{f \nu} = \frac{1}{2} \sum \frac{y_m^2}{f} \frac{n_F - n_C}{n_d - 1} \]
The quadratic difference between $\lambda$ and F wavefronts is:

$$\delta_{\lambda} W_{020} = \frac{1}{2} \sum \frac{y_m^2}{f} \frac{n_\lambda - n_F}{n_d - 1} = \frac{1}{2} \sum \frac{y_m^2}{f} \frac{n_\lambda - n_F}{n_d - 1} \frac{n_F - n_C}{n_F - n_C} =$$

$$= \frac{1}{2} \sum \frac{y_m^2}{f \nu} \frac{n_\lambda - n_F}{n_F - n_C} = \frac{1}{2} \sum \frac{y_m^2}{f \nu} P_{\lambda F}$$

Where $P_{\lambda F}$ is the partial dispersion ratio from $\lambda$ to F

For a system of thin lenses we have:

$$\delta_{\lambda} W_{020} = \frac{1}{2} \sum \frac{y_m^2}{f \nu} P_{\lambda F}$$
Thin doublet

For a thin achromatic doublet:

\[ f_a \cdot \nu_a = f_b \cdot \nu_b = F \cdot (\nu_a - \nu_b) \]

\[ \delta_\lambda W_{020} = \sum \frac{y_m^2}{fV} P_{\lambda F} = \frac{y_m^2}{F} \frac{P_a - P_b}{\nu_a - \nu_b} \]

For zero secondary spectrum:

\[ \tan(\phi) = \frac{P_a - P_b}{\nu_a - \nu_b} \]
Prof. Jose Sasian

Partial Dispersion ratio vs. Abbe number

Fluorite/crowns
Titanium glasses
Lanthanum glasses

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THE UNIVERSITY OF ARIZONA
THREE-LENS APOCHROMAT

\[ c = \frac{1}{R_1} - \frac{1}{R_2} \]

\[ \sum v_c \Delta n = \phi \] \hspace{1cm} Power

\[ \sum c \Delta n = 0 \] \hspace{1cm} Achromatism

\[ \sum P_c \Delta n = 0 \] \hspace{1cm} Secondary Spectrum

where:

\[ V_a \left( c_a \Delta n_a \right) + V_b \left( c_b \Delta n_b \right) + V_c \left( c_c \Delta n_c \right) = \phi \]

\[ \left( c_a \Delta n_a \right) + \left( c_b \Delta n_b \right) + \left( c_c \Delta n_c \right) = 0 \]

\[ P_a \left( c_a \Delta n_a \right) + P_b \left( c_b \Delta n_b \right) + P_c \left( c_c \Delta n_c \right) = 0 \]
The solution to these equations is:

\[
\begin{align*}
  c_a &= \frac{1}{FE(V_a - V_c)} \left\{ \frac{P_b - P_c}{\Delta n_a} \right\} \\
  c_b &= \frac{1}{FE(V_a - V_c)} \left\{ \frac{P_c - P_a}{\Delta n_b} \right\} \\
  c_c &= \frac{1}{FE(V_a - V_c)} \left\{ \frac{P_a - P_b}{\Delta n_c} \right\}
\end{align*}
\]

where \( F \) is the focal length of the triplet and \( E \) is:

\[
E = \frac{V_a(P_b - P_c) + V_b(P_c - P_a) + V_c(P_a - P_b)}{(V_a - V_c)}
\]

In the P-V diagram \( E \) is the ‘sag’ of the triangle defined by the points \((P_a, V_a), (P_b, V_b), \text{and} (P_c, V_c)\).
E is the ‘sag’ of the triangle defined by the points \((P_a, V_a), (P_b, V_b),\) and \((P_c, V_c).\)

P-V Glass diagram
Geometrical meaning of E
Single glass achromats

- Huyghenian eyepiece
- Maksutov meniscus
- Houghton corrector
- Field flattener
- Shupmann: dialytes (Kingslake p. 89-92)
- Shupmann medial telescope
Single glass achromats

\[ \delta_{\lambda} W_{111} = \sum \frac{\bar{y} y}{f \nu} = 0 \]

\[ \delta_{\lambda} W_{020} = \frac{1}{2} \sum \frac{y^2}{f \nu} = 0 \]
Shupman

\[ \delta \lambda W_{020} = \frac{1}{2} \sum \frac{y^2}{f \nu} \]
Other forms are possible

- See Kingslake
- Patent literature on micro-lithographic lenses
Field correctors
Chromatic correction techniques

• Achromatize all elements
• Create two effective degrees of correction to correct two aberrations
• Phantom stop technique
• Symmetry of transverse color
• Change glasses with same Nd but different Abbe number
• Buried surface
Buried surface

• Paul Rudolph 1890
• Monochromatic design
• Split lens into a cemented doublet
• Chose second lens to have same index at nd but different dispersion than first lens
• Monochromatic properties remain the same
• Change cemented interface radius to correct color
• SK-16 and F-9
Phantom stop

- Stop shift
- $\Delta \delta \lambda W020 = 0; \; \Delta \delta \lambda W111 = 2 \left( \frac{\delta y_c}{y_m} \right) \delta \lambda W020$
- In the presence of axial color lateral color can be modified
- Correct lateral color by moving the stop
- Correct axial color at that stop position
- Move the stop back to the original position
- Color correction will be maintained
Achromatization of the Monochromatic Quartet

1990 International Optical Design conference problem
Note Aldis arrangement for controlling spherical aberration
Positive air lens
Example of optimization
Shupmann medial telescope
Single glass achromat
Mangin mirror
Field lens
Tilted components

Jim Daley
Designs in the US
See his book
Willmann-Bell

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Chromatic aberration

- Monochromatic correction (may prepare for color correction)
- Chromatic correction
- Phantom stop to nullify lateral chromatic and find location to nullify axial chromatic
- Buried surface
- Use of a second interface to move location of phantom stop
- Use of the principle of symmetry to correct lateral color
- Chromatic aberrations as a black box: two aberrations; two degrees of freedom
- Chromatic variation (induced) of aberrations and use of multiple interfaces
- Sphero-chromatism
- Extreme case: all lenses are achromatic.
Sag comparison with new achromat

V-number for flint increases
V-number for crown decreases

N for crown increases
N for flint decreases

\[ f_a \cdot \nu_a = f_b \cdot \nu_b = F \cdot (\nu_a - \nu_b) \]

F=100 mm
Chromatic performance

F=\sim 1500 \text{ mm}

\sim f/V \text{ or } \sim f/60 \text{ Primary spectrum}
\sim f/1500 \text{ Secondary spectrum}
\sim f//7500 \text{ Tertiary spectrum}
Achromatic doublet

20 inch diameter
F/12
BK7
F4

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Apochromatic doublet

20 inch
diameter
F/12
FPL53
F4

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Broken apochromat

20 inch diameter
F/12
BK7
KzFS1
Tlf2

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Abbe number vs wavelength

\[ \nu = \frac{n_d - 1}{n_F - n_C} \]

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Example of double relay system
Relays for photography
Chromatic correction

f/4, f=100 mm

BK7 & F2

KZFS1  
TIF6  
PSK53A  
FPL53

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Actual system

From Ronchigram simulation

From changing the Abbe number by 3
Summary

• Glass properties
• Secondary spectrum
• Single glass achromats
• Phantom stop position
• Buried surface
• New achromat
• Apochromats