Technical Synopsis of "What's Different about Ultraviolet and Infrared Optics?" by R. Berry Johnson

Introduction:

In the paper "What's Different about Ultraviolet and Infrared Optics?" by R. Berry Johnson, the author compares and contrasts systems at either end of the optical spectrum. His intention is to provide the reader with an appreciation for the unique challenges at each spectrum as well their similarities. The paper discusses optical materials, surface finishes, fabrication techniques, housings, mounting methods, testing, cost, and alignment. It also illustrates several lens systems that show commonality between UV and IR. The information presented in this article tends to be heavy on the UV side.

Optical Materials:

Ultraviolet and infrared light lie on either side of the visible spectrum. Each is split into regions as shown in table 1. The ratio between the two is roughly 10:1.

	Wavelenght (μm)
Ultraviolet	
Near	0.4 – 0.3
Far	0.3 – 0.2
Deep	< 0.2
Infrared	
Near	0.7 – 3.0
Middle	3.0 – 6.0
Far	6.0 – 15
Extreme	> 15

Table 1: UV and IR Regions

A material's index of refraction is a function of wavelength. Some materials are transparent at particular wavelengths while opaque at others. There are fewer available materials with which to make refractive optical elements in the UV than IR spectrum while the visible spectrum has the widest selection of materials. UV light also has the disadvantage that both the maximum available material index is less and the range of indices is smaller. Available refractive materials fall off sharply for wavelengths less than 300 nm and longer than 10 μm. Additional disadvantages UV materials suffer from are high dispersion (dn/dT) and solarization (color change from exposure). IR materials are more prone to internal absorption which limits their use in high power refractive applications.

Commonly used optical materials are shown in table 2. UV materials tend to be crystalline while materials for IR can be either crystalline or glass. Chalcogenides, compounds made from group 16 element on the periodic table (including oxides), tend to transmit well in the IR.

Ultraviolet	Infrared
Fused Silica	Germanium
Calcium Fluoride	Silicon
Lithium Fluoride	Sapphire
Magnesium Fluoride	Zinc Selenide
Schott Ultran	Zinc Sulfide
	Calcium Aluminate
	Germanate
	Metal Fluorides
	Oxides

Table 2: Refractive Materials

Structural Materials:
Refractive materials used in both UV and IR systems have parameters effected by changes in temperature. The two that influence system performance the most are the coefficient of thermal expansion (CTE) and change in refractive index with temperature (dn/dT). Combined, they can produce a focal shift that is temperature dependent according to equation 1.

$$\delta = \left[\frac{-f}{(n-1)}\frac{dn}{dT} + \alpha f + \alpha L\right]\Delta T \qquad (1)$$

While focal shift is not wavelength dependant, resolution and depth of focus as established by the Rayleigh criteria are. Given in terms of numerical aperture (*NA*):

$$resolution = \frac{0.61\lambda}{NA} \qquad (2)$$

$$DOF = \frac{\pm\lambda}{NA^2} \qquad (3)$$

The result is that by carefully choosing the configuration and combination of materials with different CTE's, the focal plane's position can compensate for the focal shift due to temperature changes. As long as the error between focal plane's position and the focal shift is less than the DOF, the system is athermal. The effect of temperature on system performance is negligible. Table 3 shows resolution and DOF for two wavelengths at UV and IR.

Wavelength (µm)	Resolution (µm)	Depth of Focus (µm)
0.365	0.61	±0.71
10	12.7	±21.7

Table 3: Comparison of Resolution and DOF vs. Wavelength (NA=0.48)

IR systems can be readily corrected using passive athermalization with the correct selection of materials. While the UV system has much finer resolution, for equivalent NA, the DOF makes a passive approach to athermalization unfeasible. Most UV systems either use motors or piezo-electric devices to compensate for temperature or carefully control the environment. The appendix lists thermal dependent properties for selected materials.

Lens Configuration:

IR and UV systems can both look fairly similar. Either can use all-refractive optics, all-reflective optics, or a combination of both (catadioptric system). The diffractive optical element is currently unavailable to UV systems due to manufacturing limits on the resolution that these can be produced at. Figures 1 & 2 show similar catadioptric cassegrain optical systems. The same lens design techniques can be used for UV as for IR. In general, IR systems have a larger field of view while UV systems have tighter field flatness and less distortion.

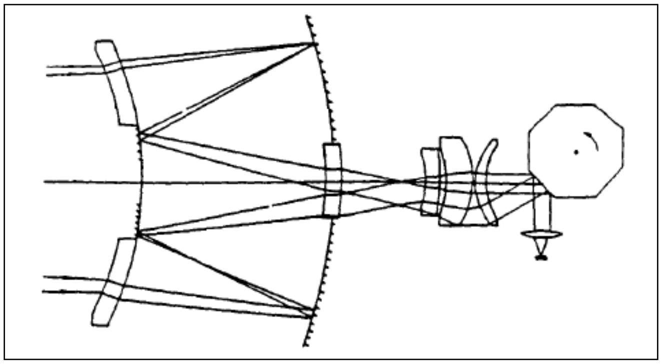

Figure 1: IR Scanner

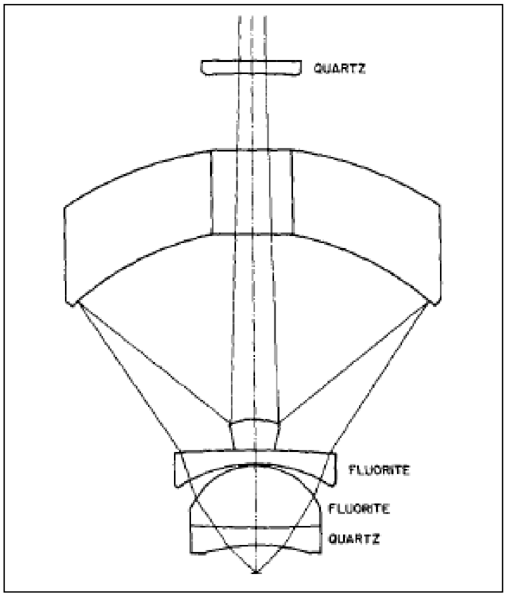

Figure 2: UV Microscope Objective

Other issues to be cognizant of is that UV systems can be sensitive to polarization and partial coherence while IR systems are susceptible to narcissus effects (detector self-imaging due to internal reflectance).

Coatings:

Most functional coatings available for visible optics are also available for IR optics. UV anti-reflective coatings are not available for wavelengths shorter than 250 nm. Below 250 nm special band-pass coatings can be had, but are expensive and difficult to produce. Reflective coatings are listed in Table 4. For wavelengths shorter than 150 nm, special reflective coatings are available for specific narrow frequency bands.

Ultraviolet	Infrared
UV Enhanced Aluminum (>150 nm)	IR Enhanced Silver
Special (<150 nm)	Gold
	Aluminum

Table 4: Reflective Coatings

Fabrication and Testing:

Light scattering by optical surfaces is due to surface roughness and wavelength. Despite having the same fundamental surface figure of $\lambda/4$, UV element surfaces must be polished to a very high quality while IR optics can be either polished or single-point diamond turned. At a wavelength of 365 nm, the surface figure is 91 nm while at 10 μm it is 2500 nm. The base substrate for a UV mirror may be diamond turned which is then followed by a nickel plate, more diamond turning, polishing to remove any tool marks, and then applying the reflective coating. The nickel plate and reflective coating need to take in to account possible CTE mismatches. Scattering due to surface roughness is given by equation 4.

$$\sigma^2 = [2\pi\Delta S_{rms}(n-1)]^2 \tag{4}$$

where σ^2 is the energy diffracted out of the central core of the point spread function and ΔS_{rms} is the rms surface error. Figure 3 shows scattering for various levels of polishing and wavelength. Unfortunately both cost and schedule increase with reduced surface roughness.

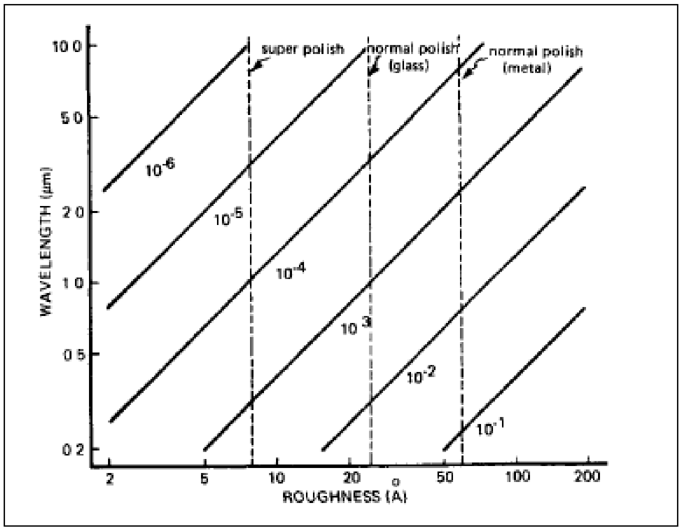

Figure 3: Theoretically predicted levels of scattered light as a function of surface roughness and wavelength covering both the ultraviolet and infrared regions.

Surface testing is also more difficult with UV surfaces since surface measuring interferometers operate at twice the frequency or greater otherwise fringe sensitivity is reduced. Also testing scattered flux in the UV must be done in a vacuum due to atmospheric absorption.

Mounts and housings for IR assemblies can be produced using conventional manufacturing techniques. Tolerances run at around 10 μm (.004 inches). UV assemblies must typically be hand lapped and diamond turned to meet tolerances on the order of 0.5 μm (.00002 inches).

Conclusion:

It appears that the main differences between ultraviolet and infrared systems arise from two factors: material availability and optical effects that scale with frequency. Otherwise the two spectrums can be analyzed the same and produce optics of similar geometries. Most of the information presented in this paper gives the impression that the design of IR optical systems is simple and straight forward compared to UV systems. What the author points out in conclusion is that this has influenced application. Many UV systems are used for lithography and sit in climate controlled clean rooms while IR is seen in many demanding military applications. One area that I felt the author failed to address is the necessity to cool many IR systems or otherwise manage radiation due to temperature.

REFERENCES:

1. R. Berry Johnson, “What’s Different about Ultraviolet and Infrared Optics?” in Critical Review Vol. CR43, Optomechanical Design, ed. P.R. Yoder, Jr (July 1992) Copyright SPIE
2. J. Berge lecture notes OPTI 521, Fall 2009

3. Appendix

Material	Spectrum	CTE (ppm/C)
Fused Silica	UV	0.5
Silicon	IR	4.2
Germanium	IR	6.1
Sapphire	UV	6.7(p)/5(s)
Zinc Selenide	IR	7.8
Chalcogenides	IR	13
Calcium Fluoride	UV	24
Lithium Fluoride	UV	37

Table 5: CTE for Selected Optical Materials

Material	Spectrum	dn/dT (ppm/C)
Silicon	IR	39
Germanium	IR	67
Calcium Fluoride	UV	-90
Lithium Fluoride	UV	-16

Table 6: dn/dT for Selected Optical Materials

Material	CTE (ppm/C)
6061 Aluminum	23.6
17-4 Stainless	10.8
Invar	0.9
Titanium Alloy	8.6

Table 7: CTE of Selected Structural Materials