Methods

Neutral density filters: theory vs. reality

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Abstract

Neutral density filters in theory do not affect the shape of the spectrum of radiation that traverses through them. In practice, real neutral density filters are far from being truly neutral and do alter the spectrum of radiation. Not all neutral density filters alter the spectrum to the same extent or in the same way. Here I compare the spectral transmittance of seven readily available neutral density filters and consider how their effect on the light spectrum can have implications for their use in light sources used in scientific research and on camera lenses used for imaging.

What is a neutral density filter?

A neutral density (ND) filter is a "grey" filter, a filter that transmits equal fractions of the incident radiation at all wavelengths—e.g. constant 50% transmittance from the far UV to the far IR. A perfectly neutral filter over such a broad range of wavelengths is an idealized concept. Even over much narrower ranges of wavelengths it is very difficult to make filters that are perfectly neutral. There are different approaches to making filters approximating colour neutrality, and each approach has different advantages and disadvantages. A "cocktail" of pigments can be incorporated into the mass of a synthetic resin or optical glass, or applied as a coating to the surface of a plastic film, or sheet of synthetic resin or optical glass. A variation on this approach is the deposition of very thin layer of metal onto the surface of optical glass under vacuum. When pigment or metal coatings are used they can be protected from scratching and damage either by an additional coating with a hard material or by enclosing the coating in-between two sheets of optical glass or synthetic resin. I here compare the spectral transmittance of seven easy to obtain ND filters of different types and prices. These filters are used as examples of different types of filters, as many different suppliers exist (Fig. 13.1).

What are neutral density filters used for?

Neutral density filters can be used, in principle, whenever there is a need to decrease the flux of radiation. Before the advent of LEDs and LED-drivers allowing easy dimming, it was common to use ND filters to adjust PAR levels during gas exchange measurements (Sestak et al. 1971). In photobiology, they are frequently used to decrease irradiance from sources that cannot be easily dimmed, such as multi-metal discharge lamps, or lamps for which dimming causes a drastic change in the emission spectrum, such as incandescent lamps. In UV-B photobiology they are less frequently used as only special types of neutral-density filters transmit at wavelengths shorter than 350 nm (e.g. UV-VIS ND Filters from Edmund Optics described as spectrally flat from 250 to 700 nm).

The shade screens used in commercial greenhouses and frequently also in experiments studying the growth and development of plants under different irradiances, are thought of as providing “neutral shade”, although in most cases they absorb some wavelengths preferentially (as discussed in Kotilainen et al. 2018).

In photography, ND filters are used when it is desired to prolong exposure time (e.g. Cameron 2009). In scientific photography accuracy of colour reproduction is in most cases required (Blaker 1978). Is important for those using photography to document results from experiments to be aware of the possible effects of ND filters on the images captured.

Filters sold for use in photography are widely available in a variety of types, qualities and prices, making it easier to exemplify the problems one needs to be aware of when using ND filters in general.

How is the strength of ND filters indicated?

The strength of filters can be measured as absorbance, which is also called optical density (OD), or as transmittance, and one of these quantities should be used to describe ND filters in scientific work. Commercially, it is also frequent to describe filters by the denominator of the fractional transmittance (T) or by the reduction of exposure value (EV) or “number of [camera diaphragm] stops” (Table 13.1). A filter labelled ND16 transmits 1/16 or the incident radiation, and is equivalent to halving the flux 4 times in succession ($2^4 = 16$), which in photography we call 4 EVs or 4 f-stops, as illustrated in the table.

Table 13.1: Strength of neutral density filters. Numerical equivalents for quantities commonly used in the commercial and scientific description of neutral density filters: optical density (OD), transmittance (T) expressed as a fraction of one, ND*nn* naming convention, number of f-stops or exposure value (EV) change.

OD	0.3	0.6	0.9	1.2	1.8
T (%)	50	25	12.5	6.2	1.6
T	1/2	1/4	1/8	1/16	1/64
NDnn	ND2	ND4	ND8	ND16	ND64
Δ EV	-1	-2	-3	-4	-6

Methods and data sources

All the data used are available in R package ‘photobiologyFilters’ version 0.5.0 (Aphalo 2015). The data for the Schott filter is from the manufacturer, while all other filters were measured by the author with a diode array spectrometer with simultaneous use of deuterium and tungsten lamps (model 8453, Agilent, Santa Clara, CA, USA). Plots were produced with R packages ‘ggplot2’ version 3.3.1 (Wickham 2016) and ‘ggspectra’ version 0.3.4 (Aphalo 2015). Photon ratios were computed in R with functions from packages ‘photobiology’ version 0.9.28 and ‘photobiologyWavebands’ version 0.4.3 (Aphalo 2015).

The selection of filters used as examples was limited to the filters the author had available at the time of writing, and it is certainly biased with respect to brands, with two very popular brands, Hoya and Lee filters not represented. The Firecrest filter was bought directly from the manufacturer, Formatt-Hitech, at `https://www.formatt-hitech.com/` in 2018. The Hitech filter was also bought directly from Formatt-Hitech, but more than 10 years ago. The Zomei filters (`https://www.zomei.com/`) were bought in 2019 from an Aliexpress seller. For the Rosco filters (`https://emea.rosco.com/en`) I used samples from swatchbooks about 10 years old, stored in darkness at room temperature.

Figure 13.1: Some of the neutral density filters described in the article, supplied by Formatt Hitech, U.K, Zomei, China and KnightX, China.

How neutral are commercial ND filters?

Many ND filters are made using absorptive optical glass or plastic resin. Prices of these filters vary widely. Some very old filters could even be composed of a film of tinted gelating sandwiched between two sheets of optical glass for protection while the very fragile gelatin-film ND filters such as Kodak Wratten #96 are still available. Filters made using coloured pigments cannot be made with constant transmittance across a broad range of wavelengths. Some of the currently available high-end filters are in contrast made by deposition of a very thin metal layer on the surface of clear glass and can provide a much more uniform light attenuating effect across different wavelengths. Carbon can also be used as a broad band light absorber. When optical glass is used as a substrate UV-B radiation is almost completely absorbed.

The comparison presented in this article is not about brands, but about technologies. I first show a Firecrest ND filter from Formatt-Hitech (OD 1.2) made from optical glass with a thin metal layer (Figure 13.2). This type of filter has been earlier used only for scientific research due to their high cost. We can observe a rather flat curve, except for very low transmittance in the ultraviolet at wavelengths shorter than 290 nm. The low transmittance in this region is most likely due to low transmittance of the optical glass used as substrate. Only ND filters in which the substrate is fused silica or special UV-transmitting glass can be neutral in the UV region of the spectrum. This filter can be considered very good, but is far from perfect: the maximum and minimum transmittance in the range 350 nm to 900 nm are 0.076 and 0.051, while the rated OD 1.2 equals transmittance equal to 0.062.

As an example of a high-quality absorptive optical glass filter we use Schott NG3. We can see that the range of wavelengths for which the transmittance is close to the nominal value is much narrower (Figure 13.3). Photography filters of high quality are usually made from either Schott or Hoya optical glass. Absorptive glass can be combined with reflective coatings to reduce the “leak” of infrared-radiation as in the top-of-the-line ND filter from Zomei, a Chinese manufacturer of photography filters (Figure 13.4).

As a first example of absorptive “HD” resin filters we use a Zomei Pro ND8 filter (Figure 13.5). The spectrum of this filter is similar to that of the Schott glass but with higher transmission in the infra-red region and more variable transmittance within the visible region. In square sizes ND filters made from synthetic resin are still frequently used as they are

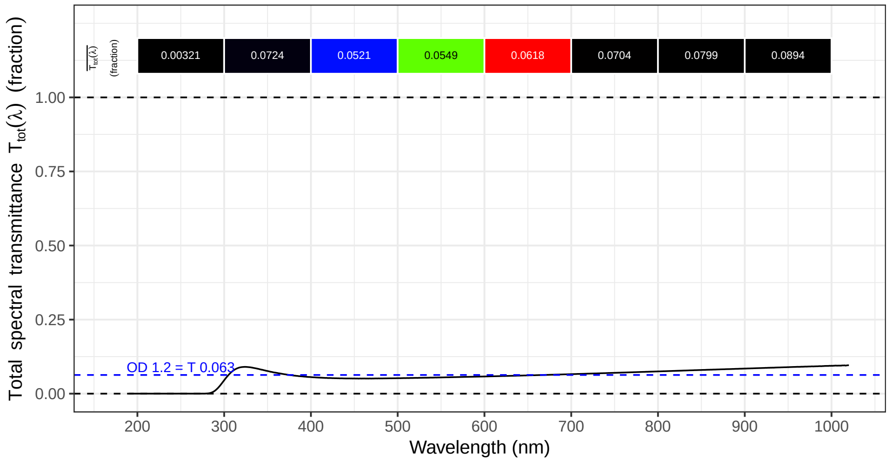

Figure 13.2: Metal deposition based neutral density filter. Transmittance spectrum of a Firecrest ND 1.2 photography filter.

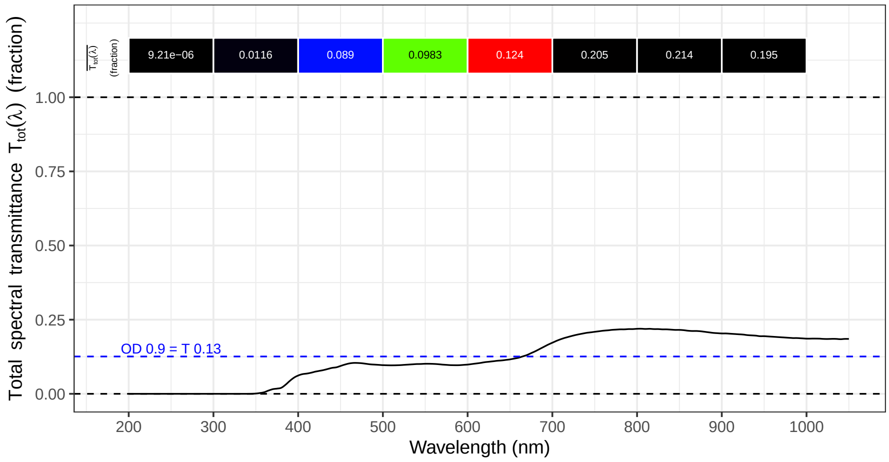

Figure 13.3: Absorptive optical glass neutral density filter. Transmittance spectrum of Schott NG3 glass at a thickness of 1 mm.

cheaper, although Firecrest filters with the same spectral transmittance as the one in Figure 13.2 are also available. As an example of a high quality filter of this type I use a Hitech filter rated at OD 0.9 (Figure 13.6). This filter has a rather flat absorptance within the visible, but very high transmittance in the infrared.

Finally we look at ND filters sold as films, usually called theatrical "gels", which one might be tempted to use to attenuate sunlight when growing plants. We use as examples a Rosco E-Colour no. E209 ND filter (Figure 13.7) and a Rosco Cinegel no. 97 grey filter (Figure 13.8). These filters are not neutral when used in sunlight as they absorb UV-B much more than visible and far-red much less than visible, in fact they are very effective filters for decreasing the R:FR photon ratio.

Angle of incidence of the light beam

All data in the examples above are for a collimated radiation beam perpendicular to the filter surface. The effect of ND filters is in-

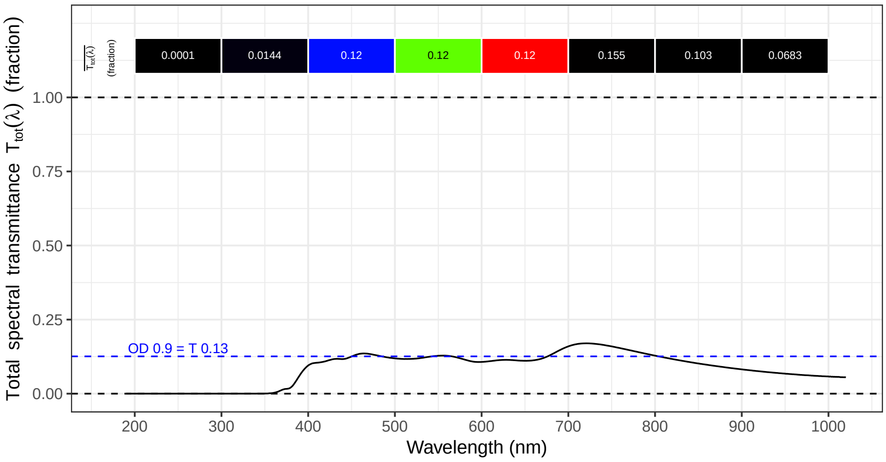

Figure 13.4: Absorptive optical glass multicoated neutral density filter. Transmittance spectrum of a Zomei Pro ND0.9 II MC filter.

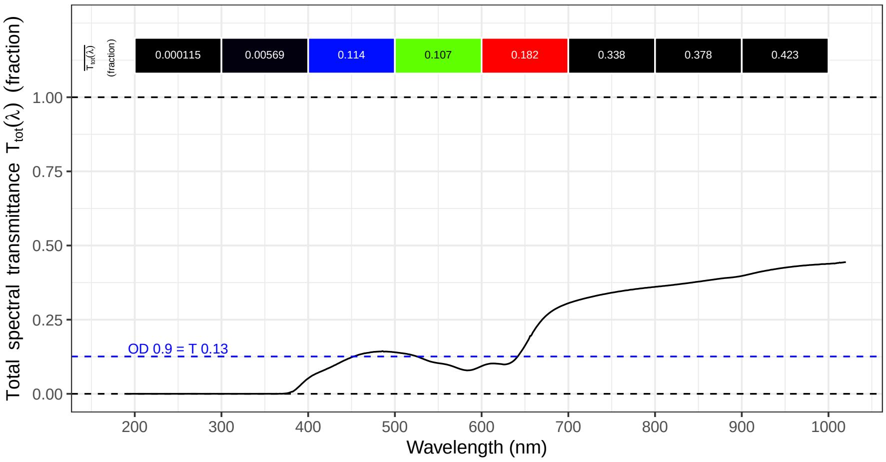

Figure 13.5: Absorptive optical resin neutral density filter. Transmittance spectrum of a Zomei Pro ND8 filter.

creased when the radiation beam's angle of incidence is shallower, as the length of the path through the absorbing medium increases. The strength of this effect depends on the type of filter, i.e. absorptive vs. reflective. It causes what in photography is called "vignetting", i.e. the darkening of the peripheral region of the image, which is most noticeable when using wide-angle objectives. When ND filters are used to attenuate irradiance, for example in radiation treatments to experimental plants, using light sources with a small emission area and a large incidence area we can get a similar effect on the edges of the light field. In cases when filters introduce colour shifts (Figures 13.2–13.8) or changes in photon ratios (Table 13.2), the magnitude of the colour shift or change in photon ratios also increase for shallower angles of incidence.

Filter aging and solarization

Exposure to strong light, both sunlight and from artificial sources, can degrade most types plastic films and sheets. Degradation usually appears as yellowing. By the time

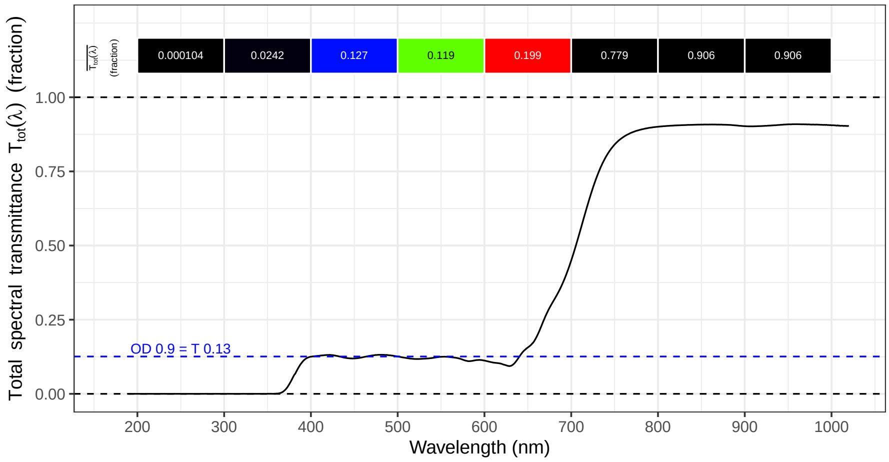

Figure 13.6: Absorptive optical resin neutral density filter. Transmittance spectrum of Hitech ND filter with OD 0.9.

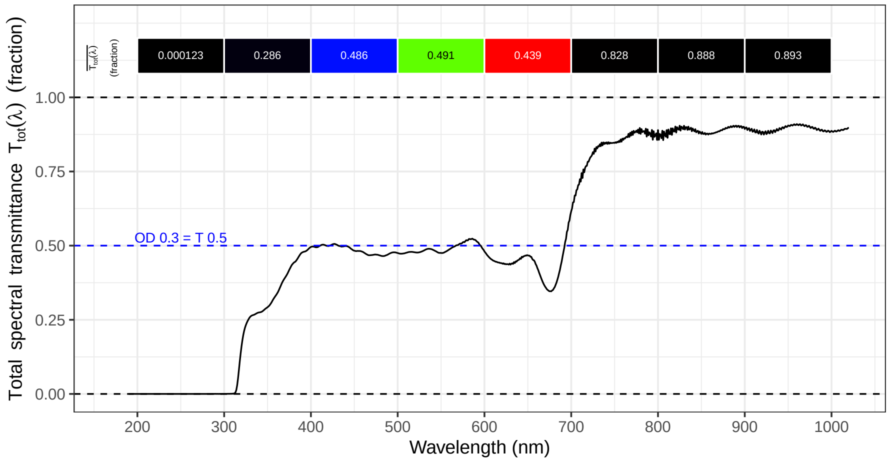

Figure 13.7: Theatrical neutral density gels. Transmittance spectrum of Rosco E-Colour no. E209 film.

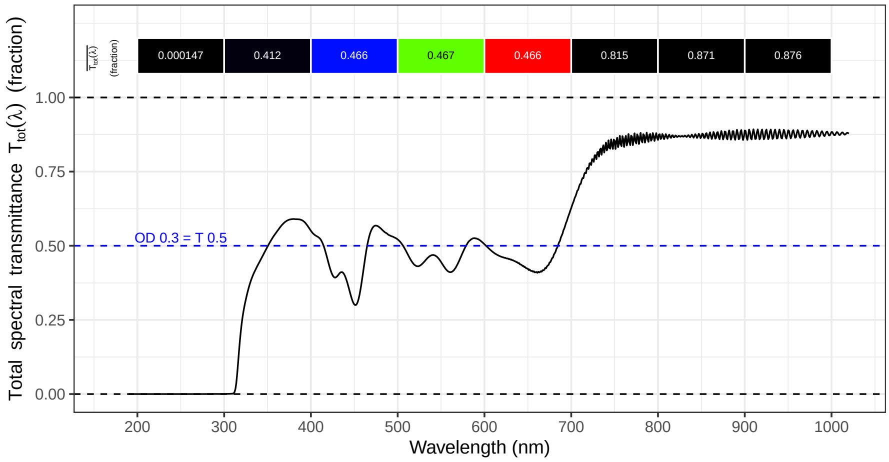

Figure 13.8: Theatrical grey gels. Transmittance spectrum of Rosco Cinegel no. 97 film.

Table 13.2: Effect of ND filters of different types on photon ratios considered important for plants. Wavelengths delimiting the different wavebands are: PAR, photosynthetically active radiation 400–700 nm; UVB, ultraviolet-B 280–315 nm; UVA, ultraviolet-A 315–400 nm; B, blue 420–490 nm; G, green 500–570 nm; R, red 655–665 nm, FR, far-red 725–735 nm. The solar spectrum used as example was simulated for 2010-06-22 near noon at Helsinki. Rows are ordered according to decreasing UVB:PAR photon ratio. The absorptance spectra of the filters are given in Figures 13.2–13.8.

Material	Filter	UVB:PAR × 1000	UVA:PAR	B:PAR	B:G	R:FR
Metal deposition	Firecrest ND1.2	2.588	0.118	0.193	0.819	1.155
—	**No filter**	**1.874**	**0.095**	**0.212**	**0.860**	**1.267**
Plastic film	Rosco Cinegel no. 97	0.065	0.105	0.203	0.853	0.646
Plastic film	Rosco E-Colour E209	0.024	0.074	0.217	0.858	0.654
Absorptive glass	Zomei ND0.9 Pro II MC	0.002	0.018	0.221	0.882	0.850
Optical resin	Zomei Pro ND8	0.001	0.006	0.195	0.923	0.813
Optical resin	Hitech OD 0.9	0.001	0.024	0.180	0.894	0.334
Absorptive glass	Schott NG3	0.000	0.016	0.191	0.825	0.773

these materials acquire a yellow tint, not only transmittance to UV radiation but also that to blue light has decreased. Although in general more stable than plastic polymers, glasses can also suffer changes in their spectral transmittance on exposure to UV and visible radiation. In the case of glasses traces of metals such as iron can determine how much their transparency changes. In the case of synthetic polymers ultraviolet radiation can break atomic bonds. In the specific case of coloured and grey plastics, the dyes used to tint the naturally clear synthetic resin may bleach when exposed to strong visible light or ultraviolet radiation.

Filters' cost and availability

Differences in price within and across different types of filters are large. I use a common size of round camera filters, 52 mm in diameter and OD of 8 to 16, or the closest value available, for the price comparison. A Firecrest filter costs 77 €, while a cheap resin one costs 4 € (spectrum not shown). Equivalent ND filters from Heliopan sell at 50 to 55 €. Zomei sells Pro ND filters made from light absorbing optical resin at 18 € for OD 8, labeled ND8 and the multicoated absorptive glass Pro II MC at 35 € . In the case of square filters, a common size is 100 × 100 mm (4 × 4 inches). The filters in this second comparison being larger, are also more expensive. A Firecrest filter costs 110 €. Edmund Scientific TECHSPEC® UV-VIS (250–700 nm) reflective neutral density filters in 50 mm diameter cost 165 €.

Optical glass ND filters are normally available in relatively small sizes of up to ca. 30 cm in diameter and 1 to 3 mm in thickness. Theatrical filter films are available in widths of up 0.6 m or 1.2 m, lengths of up to ca. 7 m, and a thickness of between 0.05 and 0.1 mm.

Implications for research in plant photobiology

As mentioned above, true ND filters are an abstraction and in practice no filter is perfectly neutral. Most commercially available ND filters have much higher transmittance in the far-red region than in the red region of the spectrum. *This means that most ND filters change both PAR irradiance and the R:FR ratio drastically.* With respect to shorter wavelengths, many ND filters will block all UV radiation or at least attenuate it to a different extent than PAR. To bring attention to these side-effects of ND filters I have computed UVB:PAR, UVA:PAR, B:G, and R:FR photon ratios in sunlight, and in sunlight filtered with ND filters (Table 13.2). One of these ND filters decreased the R:FR photon ratio to ca. 1/4 of its value in full sunlight—similarly to fairly deep vegetational shade—while all other filters decreased this ratio to smaller extents. At the short end of the spectrum, most filters strongly attenuated solar UVB radiation, with the exception of one filter that attenuated PAR more strongly than UVB (Figure 13.2) resulting in a 38% increase in the UVB:PAR photon ratio (top row in Table 13.2). The effect of the filters on the UVA:PAR photon ratio varied between a 24% increase and a 94% decrease. The filters had only a small effect on the B:G photon ratio. The unintended effects of ND filters on the photon ratios can be expected to induce strong responses in plants, which would then be confounded with those of irradiance attenuation and easily misinterpreted as an effect of a decrease in PAR. This is true at different scales, from the growth and development of plants during prolonged attenuation, to gene expression induced shortly after short-duration irradiation.

Unless objects under study are small or we intend to obtain images, shading does not need to be perfectly even in space or time. In fact shading in nature is highly variable in time and space. The easiest way of ensuring neutrality while keeping cost down is to use a material that completely blocks solar ration, but a fraction of its surface is covered by holes. Metal-wire meshes with small openings and black or silver/black scrims (e.g. Rosco E-Colour+ no. E275 or no. E270 and Lee no. 275 or no. 270) provide almost perfectly neutral shade. Black plastic shading mesh or cloth can be neutral, but its absorption outside the visible range may be different than in the visible. Finally, in the past white cotton gauze has been used for shading, but care should be taken as UV-absorbing blue-fluorescent pigments are added to most washing powders as optical whitening agents and white cloths also treated with such agents when manufactured. Depending on the distance to plants, and ventilation and or cooling or the air and lamps it may be worth considering whether the rejected radiation should be preferably absorbed or reflected. The black/silver scrims set with the aluminium coated side facing upwards will reflect rather than absorb sunlight. In the case of all these materials light is either blocked by the wires, threads, black or metal-covered film, or transmitted through open holes, which ensures that they are spectrally close to neutral. In contrast, shading materials in which the "holes" are occluded by clear plastic films are in most cases far from being neutral (Kotilainen et al. 2018), and should be in general avoided when neutral shade is the intended treatment.

Implications for imaging

Using filters that are not neutral within the range of wavelengths a camera sensor or film is sensitive to, introduces a colour cast in the images obtained. In scientific photography and reproduction, colour casts introduce a bias in the information obtained—i.e. results in bad data. In everyday photography the colour casts result in artificially looking or unnatural images. To some extent colour casts can be corrected using custom colour profiles during image processing, but in most cases correction is only partial. Normal digital cameras are sensitive to wavelengths between approximately 380–410 nm to 680–720 nm, depending on brand and model. Based on the examples shown above, in most cases the main problem is a far-red or infrared "leak", while non-neutral absorption in the range 400–600 nm is uncommon in high quality ND filters.

To avoid the introduction of colour casts when imaging in the visible, we can either use high quality ND filters like the Firecrest used as example, or stack or combine a filter that is neutral in the range 400–700 nm with an ultraviolet and IR blocking filter (Figure 13.9).

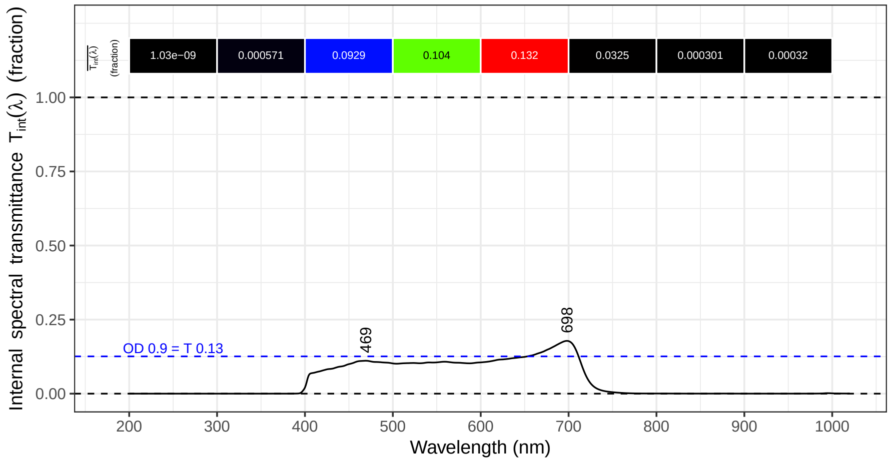

Figure 13.9: Filter "stack". Computed transmittance spectrum of Schott NG3 glass at a thickness of 1 mm stacked with a Fitrecrest UVIR Cut filter.

In photography, the second option has been the most commonly used as filters with low infra-red transmittance have been in the market for only a few years.

Conclusion

Although different in brand, thickness and manufacturer code, the filters you are likely to encounter when doing research will probably be made from similar materials and processes as those used in the examples given here, and consequently subject to similar pitfalls and limitations. When using filters in scientific research, never trust the verbal description given by manufacturers, they are usually based on the filters' function in a restricted use domain. Furthermore, when the name represents a theoretical ideal, as in the case of clear or neutral density filters, it is likely to be only an approximation to the actual characteristics of the filter. Never extrapolate from the published specifications: if behaviour at a wavelength of interest is not specified by the manufacturer, it may be different among production batches and unpredictable. Furthermore, most spectra published by filter manufacturers are described as typical and may differ from that for any given production batch. Some manufacturers will have tighter quality control than others. Filters may become mislabeled or mixed-up in our own labs and in sellers' storage. Filters from different brands, or different series or qualities within a brand, even if sold as equivalent, are frequently significantly different. Finally, the spectral transmittance of filters will frequently change in time through effect of exposure to radiation and/or to humid air and through surface oxidation. My recommendation is to measure the spectral transmittance of every filter you use in research both when new and at regular intervals afterwards, replacing as needed the degraded ones.

References

Aphalo, P. J. (2015). "The r4photobiology suite: spectral irradiance". In: *UV4Plants Bulletin* 2015.1, pp. 19–27. ISSN: ISSN 2343-323X. DOI: 10.19232/uv4pb.2015.1.14.

Blaker, A. A. (1978). *Handbook for Scientific Photography*. W H Freeman & Co. ISBN: 9780716702856.

Cameron, I. (2009). *Transient Light*. Guild of Master Craftsman Publications Ltd. 176 pp. ISBN: 1861085249.

Kotilainen, T., T. M. Robson, and R. Hernández (2018). "Light quality characterization under climate screens and shade nets for controlled-environment agriculture". In: *PLOS ONE* 13.6, e0199628. DOI: 10.1371/journal.pone.0199628.

Sestak, Z., J. Catsky, and P. G. Jarvis (1971). *Plant photosynthetic production: manual of methods*. English. The Hague: Junk, p. 819.

Wickham, H. (2016). *ggplot2*. Springer International Publishing. DOI: 10.1007/978-3-319-24277-4.

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