1. Introduction

For optical diagnostic systems, collimating or focussing collection optics are often used to couple light into a fibre optic, through which light is then transported to a detector. This gives a number of advantages, as it increases the amount of collected light, and thus the sensitivity of the system, and it allows the accurate definition of a volume from which light is collected. These systems typically comprise of a single lens, or a pair of lenses to reduce aberrations, with the fibre located at or near the focal point for the wavelength to be investigated, as shown in figure 1. The collection volume for such a system is a truncated cone with a very shallow angle of less than $1^\circ$, and an initial diameter determined by the size of the lens or any aperture stops used. The narrow observation volume and ease of construction and alignment mean these optical arrangements are particularly attractive for diagnostics of spatially varying experiments, such as optical emission spectroscopy of low pressure plasmas [1–3], which can have light emitting volumes ranging from a few centimetres to a few metres in size.

The use of a cylindrical acceptance volume within a plasma or other light source results in a volume integrated measurement of the emission. The collected light is usually taken as a uniform average of the emission along the acceptance volume, which can be moved laterally through the experiment to provide spatially resolved measurements. In taking the measurement as a uniform average, one makes the assumption that each point along the collection volume contributes equally to the collected light. Assuming the volumetric light source can be approximated by many point sources emitting in $4\pi$ sr, this corresponds to assuming that an equal solid angle is accepted...
into the detector from each source. Given that similar optical systems are used to convert fibre output into a low divergence light beam, this should be a reasonable assumption for the direction along the line of sight. These types of systems have been previously investigated using simplified simulations, mainly in an attempt to provide some spatial resolution in the axial direction \([4, 5]\). Depending on the assumptions in the models used and the optical system that was modelled, different conclusions were reached. It was found in one case that there is no dependence of the collected light in the axial direction \([4]\), and in another that one can create a region of maximum acceptance by defocussing the system \([5]\).

Results in this work are taken from two sources. An optical setup as sketched in figure 1 is used to measure the relative intensities from a point source at various locations relative to the optics. The second information source is a full 3D ray tracing simulation, benchmarked against experimental results in the next section. It includes all optical components and computes the transmission of rays through all objects in full 3D. The simulation is able to handle an arbitrary system of axisymmetric single or multi component lenses with spherical or aspherical surfaces. It does so by finding the interaction point of light rays with surfaces of the objects, and calculating the refraction of the ray using the wavelength-dependent refractive indices of the media on either side. For acceptance into a fibre, the simulation takes the core and cladding diameters and refractive indices. Once inside the core, if total internal reflection occurs at the first interaction between the ray and the core-cladding interface, then the ray is considered accepted.

2. Simulation benchmark and first results

Experimental measurements were performed for a 400 \(\mu\text{m}\) diameter 0.22 numerical aperture multimode fibre coupled to a telescope containing a 20 mm diameter spherical achromatic doublet lens with a focal length of 30 mm, located roughly 150 mm from the telescope entrance. This is a system used for beam emission spectroscopy measurements at 656 nm on the BATMAN Upgrade Test Facility \([6]\). The optical system was focussed at a distance of 8 m via back-illumination using a high intensity green LED with a peak wavelength of roughly 520 nm. The other end of the fibre was directly coupled to a Thorlabs DET110 large area photodiode. A red LED with a sub-mm active area and a peak wavelength of 624 nm was used to represent a point light source, which was moved axially and radially relative to the collection optics. At each position of the LED the photodiode amplifier voltage was recorded, which at the low intensities used is linear to the incoming photon flux. This results in a 2D map of the relative acceptance of the optical system, shown in figure 2(a). The same focussing and illumination routine was simulated using the 3D ray tracing code. Then for each location in the volume of observation a point source was modelled, emitting uniformly into \(4\pi\) sr at 624 nm. Monte Carlo integration was performed to find the solid angle of emission from the point source that is accepted into the fibre. This result is given in figure 2(b).

The results in figure 2 show that the amount of light collected from a point source within the collection volume depends in a complex manner on the location of that point, and is not well represented at all by a simple truncated cone, uniform or otherwise. In the axial direction, there is a maximum in the acceptance around 80 cm from the telescope entrance. The acceptance is non-monotonic before this maximum, and falls as a function of \(z^2\) beyond it. In the radial direction, the maximum is generally not in the centre, but located in a ring around the axis of symmetry, the radius of which is a function of the axial distance from the telescope.

As well as the unusual and unintuitive features which will be discussed in the next section, this data shows the excellent qualitative agreement between the experiment and the simulation. During the experiment it was noticed that the precise locations of the features seen in figure 2(a) were sensitive to the focussing and rotation of the fibre, indicating that irregularities during fibre or telescope manufacture could lead to changes in the results, such as a shift of the maximum acceptance off-axis by some millimetres. This is the likely cause of the slight asymmetry observed in the experimental data, despite all components supposedly being axisymmetric.

3. Image—fibre interaction

The cause of the structures seen in figure 2 was investigative by using the ray tracing simulation to calculate the illumination from a point light source at various positions in the axial \((z)\) and radial \((r)\) directions relative to the optics entrance. For these results the image of the point source at the position of the fibre was recorded, the results of which are given in figure 3. It should be noted that at the point source, random initial rays were used for these calculations, which is the source of the apparent noise or speckling in the data.

The data in figure 3 show how the structures seen in the acceptance maps in figure 2 can be attributed to the interaction between the image of the point source and the fibre.
entrance, denoted by the red circles. On the first order, there
are two competing effects at work in the axial direction. As
the point source moves away from the telescope, towards the
focal point, the image becomes smaller and a larger fraction
of the collected light falls onto the fibre entrance. At the same
time, the absolute amount of light collected by the telescope
declines, as the entrance of the telescope subtends a smaller
solid angle with the point source. These two effects cause the
non-monotonicities seen in the region between the telescope and
the maximum acceptance, which, barring other effects, is the
point at which the image of the point source is the same size
as the fibre entrance.

The precise form of the acceptance curve along the axis is
complicated further by the presence of spherical aberrations,
making it difficult to predict. These aberrations, evidenced by
the dark ring structure in the images in figure 3, play a more
significant role when the point source is moved in the radial
direction. In the case shown in figure 3, the ring structure

Figure 2. The relative amount of light collected from point sources at different axial and radial positions relative to the telescope entrance for the case of a spherical achromatic doublet lens as (a) measured in the optical setup and (b) calculated by the simulation.

Figure 3. The image of a point source in the plane of the fibre entrance. The point source emits at 624 nm and is located at various values for r and z relative to the optics entrance (see figure 1). The telescope contains an achromatic doublet lens, the same as for figure 2. The fibre core is marked with a blue circle, everything within this circle that is not dark red is accepted into the fibre. The dark red sections in the images are areas where light is falling onto the fibre, but it is not transmitted down the fibre due to the high angle of incidence. Numbers within each section give the accepted solid angle from that point in space.
causes there to be a maximum acceptance off axis, the distance of which from the central axis changes as the ring structure changes in size. The situation is complicated even further by the non-transmission of rays with high incident angles on the fibre entrance, which reduces the accepted solid angle by some amount.

4. Wavelength dependence

As the lens used in the investigation is achromatic, it would be expected that a change in wavelength has a minimal effect on the acceptance of the system, and figure 4 shows that this is partly true. The focusing is not affected by the wavelength of the light source, and so the features seen in figures 4(a) and (b) are in the same locations as in figure 2(b). However the wavelength does affect the spherical aberrations that occur, as can be seen in figure 5, which shows how the image of the point source is altered by changing the wavelength to 400 nm. It can be seen that the dark ring structure previously observed in figure 3 has moved toward the centre of the image for 400 nm, and is broader in size. This corresponds with the broadening of the radially dependent features seen in figure 4(a).

In addition to the changes in spatial features, there are also differences in the absolute values of accepted solid angle across the volume at different wavelengths. Therefore even if

Figure 4. The relative amount of light collected by the same systems as in figure 2 from point sources with wavelengths (a) 400 nm and (b) 520 nm.

Figure 5. The same as figure 3 but for a source emitting at 400 nm.
Figure 6. The relative amount of light collected by a fibre coupled with an aspheric lens from point sources with wavelengths (a) 400 nm, (b) 520 nm, and (c) 624 nm.

Figure 7. The relative amount of light collected by a fibre coupled with an aspherized achromatic lens from point sources with wavelengths (a) 400 nm, (b) 520 nm, and (c) 624 nm.
one were to compensate for the changes in spatial distribution of the acceptance, the intensity response of the system would still vary as a function of wavelength. This may affect diagnostic systems that use ratios of emission lines, as is often performed with optical emission spectroscopy of plasmas.

5. Investigation of other optical systems

In order to further investigate the features observed, three other systems were implemented in the ray tracing simulation and their acceptance maps calculated. These systems were:
- Direct exchange of the achromat with an aspheric lens
- Direct exchange of the achromat with an aspherized achromatic doublet lens
- A Thorlabs F810SMA635 off-the-shelf collimator package

These systems were all focussed at infinity, using 520 nm light for the two lenses, and the design wavelength of 635 nm for the F810SMA635.

For each of these systems, the acceptance plot was calculated for different wavelengths. The results for the aspheric lens are given in figure 6 for wavelengths of (a) 400 nm, (b) 520 nm, and (c) 624 nm. It can be seen that this lens has a heavy wavelength dependence, as each plot shows completely different characteristics. For 400 nm the collection is focussed in a small spot around 50 cm from the telescope. This is the point at which the image of the point source is 400 nm in diameter, the same as the core of the fibre. At the focussing wavelength, 520 nm, there is a triangular region close to the telescope within which the acceptance is uniform. This shows that there are no spherical aberrations, as there is no radial dependence. The uniformity in the axial direction shows that the two competing effects of changes in source image size and varying subtended solid angle cancel exactly within this region. Beyond the point of this triangular region, where the image is smaller than the fibre entrance, the accepted solid angle decreases with axial distance squared, as would be expected from a dependence purely on the solid angle subtended by the telescope entrance. For 624 nm the behaviour is different again, with a constantly decreasing acceptance as the axial distance increases, and very little radial dependence. The rate of change of point source image size is different in comparison with 520 nm, and so the two effects previously mentioned no longer cancel.

The results for the aspherized achromatic lens are shown in figure 7 for wavelengths of (a) 400 nm, (b) 520 nm, and (c) 624 nm. Here it is seen that there is very little difference between the results for different wavelengths, and figures 7(b) and (c) are nearly indistinguishable. Some residual spherical aberrations cause the features to be smeared out somewhat at 400 nm, as seen in figure 7(a). These results show that, if the volume from which light is to be collected fits within the first...
triangular region, then the assumption can be made that the volume is sampled uniformly. If the volume to be observed is far away, beyond the maximum acceptance, then it can be assumed that the light collected falls as the distance squared. These assumptions hold for a wide range of wavelengths within the visible range. It is likely that lens systems designed for different wavelength ranges would only satisfy these conditions within their design specifications.

The use of an off-the-shelf collimator package as a collection optic is tempting, as these systems are designed to produce accurate Gaussian beams with very low divergence angles when back-illuminated from the fibre. The assumption of reversibility in the optical system suggests that light is therefore collected from a line of sight with a very shallow angle of expansion. For this reason one such item was investigated in the same manner as the other systems, but focussed at infinity using 635 nm light, as it is designed for. The results for this system are given in figure 8 for (a) 400 nm, (b) 520 nm, and (c) 635 nm. It can be seen that this system also has severe dependencies on the wavelength of the incoming light, and the ‘uniform triangle’ seen in other systems is limited to 635 nm, the wavelength for which the collimator is designed. Spherical aberrations also affect the results for 635 nm, as the ‘uniform triangle’ does not sample the volume completely equally, but still has some axial and radial dependence. The shorter wavelengths exhibit very different behaviour, each with a well defined location from which most light is accepted.

6. Discussion and consequences

The spatially resolved acceptance within the line of sight defined by an optical system comprising one or more lenses focussing light onto an optical fibre was investigated using a ray tracing simulation and experimental measurements. It was found that, contrary to the definition of a single acceptance angle for the optical system, the solid angle recorded from a point source varied non-monotonically and non-intuitively as it was moved axially and radially relative to the entrance of the optical system. Changes in the recorded solid angle were found to stem from the interaction between the finite sized image of the light source and the finite sized fibre entrance. The precise behaviour was identified to depend heavily on the type of lens used in the optical system, and differences were observed between spherical and aspherical lenses. All investigated lens systems exhibited defined regions in the acceptance map where the behaviour was different, separated by a maximum some distance from the optical system. This maximum acceptance was notably not at the focal point of the optical system, but at some closer distance defined by the finite diameter of the fibre.

These results show that reversibility for this type of optical system cannot be assumed, which is done when they are analysed by back-illumination. In the case of light emanating from the fibre with a roughly uniform distribution over the solid angle, the back of the lens(es) receives a roughly 2D Gaussian in light intensity. This light is then parallelised by the lens and a Gaussian (or similar) beam emerges. When light is emitted from a point source and falls on the front of the lens, furthest from the fibre, this point source is then imaged onto the fibre or back wall of the telescope. Depending on the position of the point source within the line of sight, this image will be of different sizes, different intensities, and in different positions relative to the fibre. The interaction of this image with the fibre entrance causes the solid angle accepted from each point to change, and the addition of aberrations within the lens system further complicates this effect.

These results have significant implications for any experimental setup with these type of optical systems that make observations of a non-uniform light source, or that otherwise rely on knowing the position in space from which light is collected. For these systems, the assumption of a single acceptance angle or cone is not valid, nor is it sufficient to make simplifications, such as the thin lens approximation, when modelling these systems. Instead, the full three dimensional behaviour of light through the system should be modelled, the acceptance (or not) of which may additionally be highly sensitive to focussing and irregularities in manufacture of the lens system or fibre entrance. The observed behaviour is a property of the interacting variable-sized image and fibre entrance acting as an aperture, and occurs even in the absence of aberrations. Therefore while there may be optical systems that allow for approximations under certain use cases, it is probable that all optical collimators are subject to this phenomena. It is suggested that, if possible, observation systems are designed such that light is collected from beyond the point where image size and fibre size coincide, and behaviour can be better approximated by a cone of observation.

Although the results shown make line of sight type observations difficult, these effects could be used for targeting the acquisition volume to a specific region, as suggested by Li et al [5]. However, care should be taken due to the sensitivity of the systems to changes in wavelength or slight misalignments of the fibre. Should such a technique be attempted, it is highly recommended that direct measurement with a point source is undertaken after focussing is performed.

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References

[1] Boileau A, Von Hellermann M, Horton L D, Spence J and Summers H P 1989 The deduction of low-Z ion temperature and densities in the JET tokamak using charge exchange recombination spectroscopy Plasma Phys. Control. Fusion 31 779–804

[2] Swindells I, Kelly P J and Bradley J W 2008 Spatially-resolved optical emission from a bi-polar pulsed DC magnetron discharge Surf. Coat. Technol. 203 391–5

[3] McKee G, Ashley R, Durst R, Fonck R, Jakubowski M, Tritz K, Burrell K, Greenfield C and Robinson J 1999 The beam emission spectroscopy diagnostic on the DIII-D tokamak Rev. Sci. Instrum. 70 913–6

[4] Siepa S and Czarnetzki U 2015 Line integration and spatial resolution in optical imaging of plasmas J. Phys. D: Appl. Phys. 48 385201

[5] Li T, Sheta S, Hou Z, Dong J and Wang Z 2018 Impacts of a collection system on laser-induced breakdown spectroscopy signal detection Appl. Opt. 57 6120

[6] Fantz U, Bonomo F, Froschle M, Heinemann B, Hurlbatt A, Kraus W, Schiesko L, Nocentini R, Riedl R and Wimmer C 2019 Advanced NBI beam characterization capabilities at the recently improved test facility BATMAN Upgrade Fusion Eng. Des. 146 212–5