Monte Carlo simulations for estimation of backscattered light intensity using an optical source-detector fibre array probe on convex Delrin pieces

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Background
In a previous study (Sundberg et al. 2004) we presented a new technique for representation of surface shape. A fibre optical sensor based on parallel arrays of source and detector fibres yielded a source-detector intensity matrix (SDIM). In that study, it was shown that the technique could distinguish accurately between different convex and concave surfaces made from Delrin (DuPont, Wilmington, USA). A simplified simulation of the SDIM was provided, assuming backscattered light to be described as Lambertian sources at each element of a discretized illuminated surface. These simulations showed discrepancies compared to the measured data, probably due to the simplifications in the model for light scattering. In this study we have performed Monte Carlo simulations from which the SDIM-s have been calculated.

Materials and Methods
Five Delrin pieces with spherically symmetric surfaces of different radius of curvature were created; four with convex surfaces (with 20, 30, 40 and 50 mm radius of curvature) and one with a plane surface, serving as reference. Surface shape measurements were performed utilizing an optical fibre array sensor, described in detail elsewhere (Sundberg et al. 2004), see figure 1.

By means of an oblique angle illumination technique (Jacques et al. 1995) the reduced scattering coefficient of Delrin were determined. Here (figure 2), laser light is incident on the object at an angle oblique to the surface normal (45°). The 2D backscattered intensity profile, as measured by a CMOS digital camera, shows a hot spot at the point of incidence and a diffuse spherical symmetric backscattered profile. It is assumed that the diffuse profile can be described as an isotropic point source centred at a distance of 1/µs' from the surface along the optical axis of the laser beam (refracted at the air-Delrin interface). Hence, the reduced scattering coefficient can be determined by calculating the distance from the hot spot to the centre of gravity in the image from the camera.

The anisotropy factor of Delrin was determined in a goniometry set-up (figure 3), where the angular intensity profile of light transmitted through a Delrin slab 0.15 mm in thickness was measured. Monte Carlo Simulations were fitted to measurements utilizing the known reduced scattering coefficient of Delrin (from oblique angle results) and g-values ranging from 0.70-0.95 in steps of 0.05. The Henyey-Greenstein phase function was applied in the simulations.

A fibre-cladding method (Bolin et al. 1989) was employed to estimate the refractive index of Delrin. A commercial optical fibre was prepared by stripping the cladding and replacing it with Delrin. The cone of acceptance, and hence the numerical aperture of the constructed waveguide was measured by means of goniometry (figure 4).

The absorption coefficient of Delrin, 0.0017/mm was taken from the literature (Berg).

Simulations
The Monte Carlo source code was modified MCMC code where tailor made handling of the output profile of the optical fibres, the geometry of the Delrin object, total internal reflection and refraction at the Delrin/air boundary were added. Each of the 11 lights in the fibre optical array sensor was treated separately in 11 simulations. One million photons were launched for each source fibre position. Around 80 % of the photons were backscattered through the spherical cap of the Delrin and hence detectable, depending on detector position. Position, direction and total path length travelled in the turbid medium were logged for photons exiting the spherical cap. The number of logged photons that were seen, and hence detectable, by each of the 11 detectors in the optical fibre array sensor was calculated and a source-detector intensity matrix corrected for each surface.

Results
The reduced scattering coefficient, as measured by utilising the oblique angle method, of Delrin was 2.34/mm. The anisotropy factor was calculated to 0.87 in a fitting process where data from Monte Carlo simulations fitted to the experimental goniometric data (figure 5). The refractive index was 1.48.

In table 1, a summary of the optical properties of Delrin is shown, whereas figure 4 shows the results from measurements and simulations of the SDIM representing the shape of the surfaces of the four different Delrin objects. Simulated and measured SDIM-s seems to be in closer agreement than in the previous study, but further analysis is needed to quantify these measurements.

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