Complex refractive index of Intralipid and milk cream by instrument-corrected critical-angle refractometry

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Self-published preprint, not peer-reviewed. Text and figures © 2026 Ierotheos Katsoulis, licensed CC BY 4.0; analysis code MIT-licensed. Measurements were made at the Electronic Devices and Materials Laboratory (EDML), Department of Electrical and Electronic Engineering, University of West Attica, during an MSc by Research supervised by Prof. Konstantinos Moutzouris (2020–2021). The full measurement dataset may be the property of EDML, UNIWA and is not disclosed; a representative sample is provided for verification and is not covered by the CC BY license. *Cite as:* I. Katsoulis, "Complex refractive index of Intralipid and milk cream by instrument-corrected critical-angle refractometry," self-published preprint, November 2026.

Abstract

The refractive index of an undiluted Intralipid emulsion at 25 °C is 1.3691, 1.3595 and 1.3515 at 532, 964 and 1551 nm (±0.0008, relative to air). TE and TM light give the same value within 4×10^{-4}. A companion analysis of the same scans finds that the choice of reflectance model widens the uncertainty to about ±0.002 at 532 and 964 nm.

We obtained these values from 115 air-normalized critical-angle reflectance profiles taken with a prism coupler. The extended derivative method was applied after correcting for three instrumental effects calibrated independently on water: the angular spread of each laser, the angular sampling and smoothing of the analysis, and an index offset tied to the direction of table rotation. Together the corrections raise n by 0.0010–0.0012 relative to the plain derivative method. Two air-normalization protocols give the same result within 4×10^{-4}.

Milk cream (35 % fat) does not yield a reliable index from the same analysis. Its reflectance edges are two to six times wider than any homogeneous Fresnel profile, its TE and TM results differ by 0.007–0.018, and the apparent dispersion is non-monotonic. We attribute this to an inhomogeneous layer at the prism surface, and identify which measurements would be needed to characterize it.

1. Introduction

Intralipid and milk products are standard turbid samples. They are used as tissue phantoms and as food-quality targets, and their refractive index enters every light-transport model of them. Measuring that index without diluting the sample is hard, because absorption and scattering round the reflectance edge on which critical-angle refractometry relies [1–3].

The extended derivative method (EDM) addresses this. From the angle θ_c and the reflectance R_c at the maximum of $dR/d\theta$, it returns both the real index n and the extinction coefficient k [4, 5]. Related approaches fit the whole reflectance curve [6–8]. All of them assume an ideal instrument: a perfectly collimated beam, an exact angle scale, and a derivative that is not distorted by sampling or smoothing.

In a companion study on water we found that this assumption fails at the 10^{-4} level. On our prism coupler, the angular spread of each laser and the discrete sampling bias the derivative-method index by $3.5–6 \times 10^{-4}$, differently for TE and TM. The direction of table rotation adds an offset of $\pm 5 \times 10^{-4}$ [9]. Here we carry these water-calibrated corrections over to Intralipid and milk cream, measured in both polarizations at up to five wavelengths. Because both samples are isotropic, agreement between TE and TM is a built-in test of the whole analysis.

2. Method

Each medium scan is turned into an absolute reflectance profile, reduced to one pair (θ_c, R_c), and inverted for (n, k) with a model that includes the instrument.

Air normalization. With an empty cell, air (n ≈ 1) is totally reflected over the whole scan range (internal angles 31–62°, above air's critical angle of about 30°). An air scan therefore records the instrument's response alone, and

$$R(\theta) = \frac{I_{\mathrm{medium}}(\theta)}{I_{\mathrm{air}}(\theta)}$$

is the absolute reflectance of the prism–medium interface. In the slow protocol each medium scan is paired with the air scan of the same number from the series taken just before it. In the fast protocol, several medium scans share one air scan of the same wavelength and polarization, the nearest in time.

Edge parameters. R(θ) is differentiated with a quadratic Savitzky–Golay filter [13]. A coarse pass (0.6° window) locates the edge robustly against noise. The final window is max(0.055°, 0.15 × edge width), so it scales from about 0.06° for Intralipid to 0.3° for cream. θ_c is the maximum of dR/dθ, refined by a parabola, and R_c is the smoothed reflectance at θ_c.

Inversion. We solve numerically for the (n, k) whose model profile has its derivative maximum at θ_c with reflectance R_c. This is the condition of the extended derivative method [4], applied here to the full Fresnel equations for TE or TM. Three versions are compared:

1. **SDM:** $n = n_p \sin\theta_c$, ignoring k.
2. **EDM:** ideal instrument (no angular spread, fine sampling).
3. **Corrected EDM:** the model profile is convolved with the laser's angular spread σ, sampled at the measured step and smoothed with the same window as the data. θ_c is first shifted for the rotation offset.

Instrument corrections from water [9]. The angular spread is σ = 0.021°, 0.014°, 0.025° and 0.024° at 532, 633, 964 and 1551 nm; at 450 nm, where no water data exist, we assume 0.020 ± 0.010°. All turbid scans were taken with the table rotating in direction R. In water, R-direction scans read low by $(n_L - n_R)/2 = 5.0–5.3 \times 10^{-4}$, i.e. by 0.020° in θ_c. We add this angle back.

Plateau re-normalization. In some runs the medium and air scans differ slightly in laser power or alignment, so the normalized total-reflection plateau departs from its expected value by up to 10 %. We rescale each R(θ) so that its median 1.5–3° above θ_c equals the model's, and re-solve, iterating twice. This mainly changes k; n moves by less than 2×10^{-4} for Intralipid.

Quality rules. A scan is excluded if no Fresnel profile reaches its (θ_c, R_c), which happened for 3 of 115 scans. Within each group, values more than five robust standard deviations from the median are rejected (6 scans). As diagnostics we record the TE–TM difference and the ratio of measured to model edge width.

3. Samples and measurements

All scans were taken at 25 °C between 27 January and 31 March 2021 on the Metricon 2010/M prism coupler [11] used for the water study, with the same prisms (n_p = 1.9975, 1.9775, 1.9642, 1.9450 and 1.9340 at 450, 532, 633, 964 and 1551 nm).

The samples were an undiluted Intralipid emulsion and milk cream with 35 % fat. Each was loaded into the cell with a syringe after the air series, and the cell was cleaned and dried between series.

Sample	λ (nm)	Protocol	Date (2021)	TE / TM scans	Used
Intralipid	532	slow	11 Feb	5 / 5	3 / 5
Intralipid	964	slow	10–11 Feb	6 / 6	5 / 6
Intralipid	964	fast	9 Feb	5 / 4	5 / 4
Intralipid	1551	slow	10 Feb	5 / 5	5 / 5
Intralipid	1551	fast	9 Feb	5 / 5	5 / 5
Cream	450	slow	31 Mar	6 / 5	5 / 5
Cream	532	fast	27 Jan	12 / 10	10 / 7
Cream	532	slow	29 Mar	1 / 0	1 / 0
Cream	633	slow	30 Mar	5 / 5	5 / 5
Cream	964	slow	29 Mar	5 / 5	5 / 5
Cream	1551	slow	23 Mar	5 / 5	5 / 5

Table 1. Medium scans per sample, wavelength and protocol; each has matching air scans.

Wavelength of the Intralipid 532 nm series. The files of this series carry "633" in their internal names but the instrument applied the 532 nm prism index. The data show the series was taken at 532 nm. Read as 532 nm, its index (1.3691) lies 0.0096 above the 964 nm value, close to water's dispersion over the same range (0.0108). Read as 633 nm with the wrong prism index, it would give 1.3598, the same as at 964 nm, which no aqueous emulsion can show.

4. Results

4.1 Reflectance profiles

Intralipid has a sharp edge that the Fresnel model reproduces near θ_c; cream has a smeared edge that no Fresnel profile matches (Fig. 1). For Intralipid the measured derivative peak is 0.9–2.2 times (median 1.7) as wide as the model at the solved (n, k). Below θ_c the measured reflectance lies 0.05–0.07 above the model in both polarizations, the signature of diffusely back-scattered light (Section 5). For cream the edge is 1.7–6.3 times wider than the model and spreads over 2–4°.

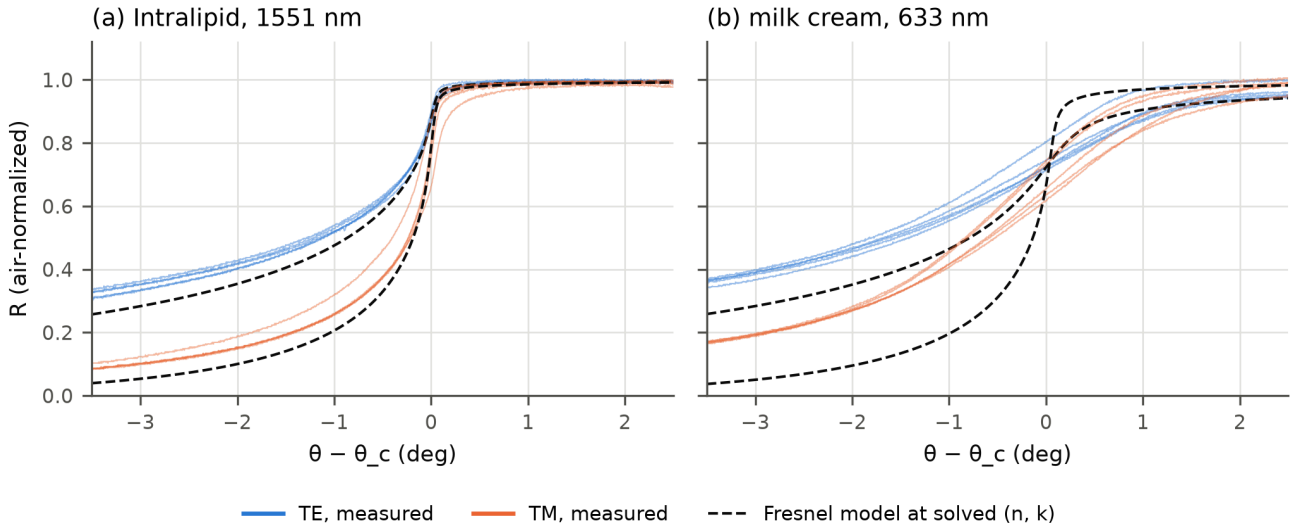


Fig. 1. Air-normalized reflectance of all TE (blue) and TM (orange) scans of (a) Intralipid at 1551 nm and (b) cream at 633 nm, with the Fresnel profiles at the solved (n, k) including the instrument's angular spread (dashed).

4.2 Intralipid

The refractive index of Intralipid at 25 °C is 1.3691 at 532 nm, 1.3595 at 964 nm and 1.3515 at 1551 nm (Table 2, Fig. 2). TE and TM agree within 4×10^{-4} at every wavelength, and the fast and slow protocols agree within 4×10^{-4}. Scan-to-scan scatter is $1–10 \times 10^{-4}$.

λ (nm)	SDM	EDM	Corrected EDM, TE	Corrected EDM, TM	n (combined)	k (indicative)
532	1.3679	1.3684	1.3691	1.3692	**1.3691 ± 0.0008**	9×10^{-4}
964	1.3585	1.3589	1.3596	1.3594	**1.3595 ± 0.0008**	5×10^{-4}
1551	1.3504	1.3508	1.3517	1.3514	**1.3515 ± 0.0008**	5×10^{-4}

Table 2. Intralipid at 25 °C, relative to air. SDM and EDM are averages over all scans; the corrected columns combine both protocols. The uncertainty is absolute and is dominated by session calibration (Table 3).

The corrections raise n by 0.0010–0.0012 relative to the plain derivative method. Of this, the EDM's attenuation term contributes 0.0004–0.0005, the rotation-direction offset 0.0005, and angular spread with smoothing 0.0001–0.0002. Without the rotation correction the Intralipid values would sit 5×10^{-4} low.

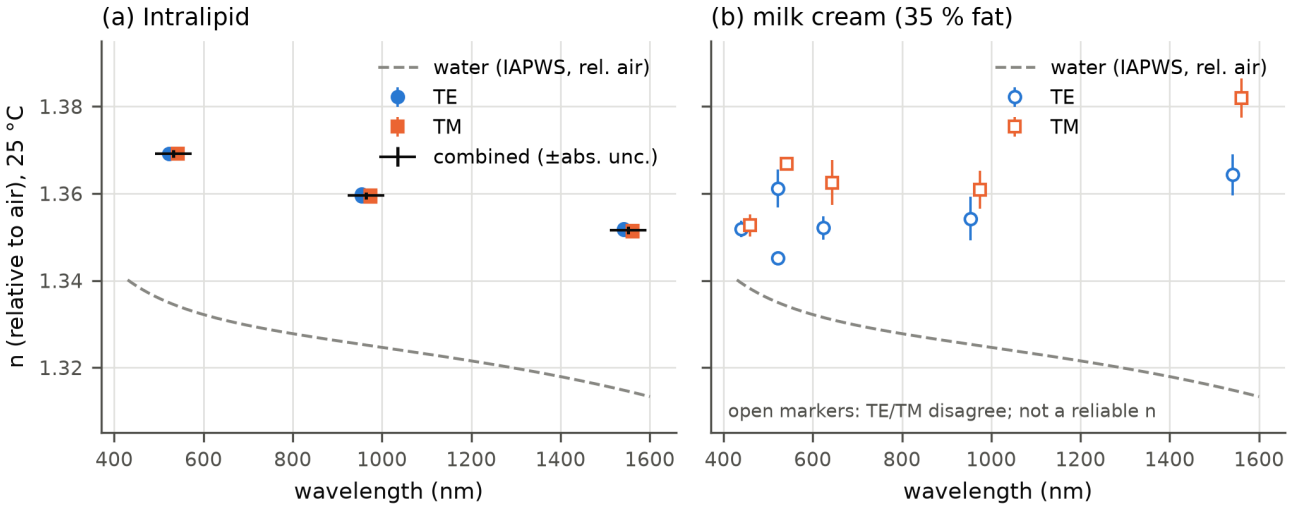


Fig. 2. Refractive index versus wavelength at 25 °C for (a) Intralipid and (b) milk cream, by polarization (bars: scan-to-scan standard deviation). Black bars in (a): combined value with absolute uncertainty. Dashed: water (IAPWS R9-97 [12], relative to air) for reference.

4.3 Milk cream

The same analysis gives no consistent index for cream. TM exceeds TE by 0.0008 at 450 nm, 0.0056 at 532 nm, 0.010 at 633 nm, 0.0067 at 964 nm and 0.018 at 1551 nm, against ≤ 4×10^{-4} for Intralipid. The scan-to-scan scatter is 0.002–0.005. The apparent dispersion is non-monotonic: the 450 nm value (1.352) is below the 532 nm values (1.345–1.367), and the 1551 nm values (1.364 and 1.382) lie above those at 964 nm (1.354 and 1.361). The individual values range from 1.345 to 1.382; we do not report them as refractive indices.

5. Discussion

5.1 Uncertainty of the Intralipid indices

The calibration uncertainty of ±0.0008 is set by the instrument, not by the turbid sample. At 532 and 964 nm the reflectance model adds a larger term (see below).

Contribution	Size (10^{-4})	Basis
Session calibration (absolute)	8	rms deviation of water from IAPWS across sessions [9]
TE–TM difference (model adequacy)	0.5–2	half the measured TM − TE
Statistical	1–3	standard error over scans and protocols
Rotation-offset transfer	1	spread of the water values; same rotation settings assumed in 2021
Angular-spread correction	1	σ from 2020 water data
Total	**8**	quadrature sum

Table 3. Uncertainty budget for the Intralipid indices.

The relative values are better known than the absolute ones. The dispersion between wavelengths is uncertain by about 3×10^{-4} plus the difference in session offsets. An index standard measured in each session would reduce the absolute term to the 10^{-4} level.

Model dependence. A companion analysis of the same scans [15] fits the whole reflectance edge with two models that include diffusely back-scattered light. Their n values differ from those in Table 2 by up to 2×10^{-3} at 532 and 964 nm and by 2×10^{-4} at 1551 nm. Including this term, the uncertainty is about ±0.002 at 532 and 964 nm and stays ±0.0008 at 1551 nm.

5.2 Plausibility

As a rough check, the coherent index of a dilute emulsion is close to the volume-weighted mean of its phases [3]. For Intralipid 20 % (about 22 % oil by volume), with soybean oil n ≈ 1.47 (approximate handbook value) and an aqueous phase close to water, this gives roughly 1.366–1.368 near 532–589 nm. That is within about 0.003 of our 1.3691 at 532 nm. A 30 % emulsion would give about 1.38. The sample was indeed Intralipid-20 %; a 2021 lab note that gives "25 % fat" is in error. The check is approximate: it ignores particle-size effects and the oil's exact dispersion. Dong et al. measured n = 1.36704 at 660 nm on undiluted Intralipid-20 % by reflectance fitting [8]. Dispersion fits through our three wavelengths give 1.363–1.368 there, which includes their value [15]. The values of Ding et al. at 532 and 1557 nm [10] have not yet been compared.

5.3 Diffuse reflectance and the meaning of k

Below θ_c, light enters the emulsion and part of it is scattered back into the prism. This diffuse component adds to the coherent Fresnel reflectance, which is why the measured Intralipid profiles lie 0.05–0.07 above the model there (Fig. 1a) [10]. Close to θ_c the coherent term dominates, so n, which is set mainly by the edge position, is robust. R_c and therefore k absorb part of the diffuse term. The k values ($5–9 \times 10^{-4}$) should be read as effective coherent-attenuation coefficients, not as material constants. A full-edge analysis that models the diffuse light gives k 1.2–4 times larger [15].

5.4 Why cream fails

Cream breaks three assumptions of the method at once. The edge is far wider than any Fresnel profile, TE and TM disagree by up to 0.018, and the apparent index does not fall monotonically with wavelength. A homogeneous medium with a single complex index cannot produce this combination. Two mechanisms near the prism surface could. Fat globules (n ≈ 1.46) can adsorb on the prism and form a high-index layer, which raises the apparent index and affects TE and TM differently. Creaming in the cell over the minutes of a series would also change the composition next to the prism from scan to scan. Models of total reflection from highly turbid media with such layers [6, 7, 14] would be needed, together with measurements that control them: a fresh sample for every scan, a cleaned prism between polarizations, and repeated scans to track drift.

6. Conclusions

Instrument-corrected critical-angle refractometry gives the refractive index of undiluted Intralipid-20 %: 1.3691, 1.3595 and 1.3515 at 532, 964 and 1551 nm (25 °C, relative to air), with uncertainties of about ±0.002, ±0.002 and ±0.0008.

1. Corrections calibrated on water (angular spread, sampling and smoothing, rotation direction) raise the index by 0.0010–0.0012 over the plain derivative method. The rotation offset alone is 5×10^{-4}.
2. TE and TM agree within 4×10^{-4}, and the two air-normalization protocols agree within the same margin, so the analysis is internally consistent.
3. The extinction coefficient from the extended derivative method absorbs diffusely back-scattered light and is biased low, by up to fourfold for this emulsion [15].
4. Milk cream with 35 % fat does not behave like a homogeneous absorbing medium at the prism, and the method does not give it a defined refractive index. Its TE–TM disagreement (up to 0.018) is a simple, built-in test that flags this.

At 1551 nm the limiting uncertainty is the session-to-session calibration of the instrument; at 532 and 964 nm it is the reflectance model [15]. Measuring an index standard in each session would bring the absolute uncertainty close to the 10^{-4} level that the relative data already reach.

Known open issues

- Compare with the values of Ding et al. [10] (paywalled; university access needed).
- Confirm that "R" in the turbid file names means the same rotation direction as in the 2020 water files.

Data and code

A representative sample of the raw scans is provided with this release for verification (`data_sample/`, 16 files: water at 964 and 1551 nm in both polarizations and rotation directions, Intralipid at 1551 nm and cream at 633 nm with their air references). The full dataset (252 water scans, and 115 Intralipid and cream scans with their air references) was recorded at EDML, UNIWA; it may be the property of the laboratory and is not disclosed. The complete analysis code is included (`code/`): it reproduces every number in this paper when run on the full dataset, and processes the sample files individually.

Measurements: Ierotheos Katsoulis, Electronic Devices and Materials Laboratory (EDML), University of West Attica, during an MSc by Research supervised by Prof. Konstantinos Moutzouris. Analysis and text: Ierotheos Katsoulis, 2026.

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