A Reflectance Probe to Measure Sea Ice Inherent Optical Properties

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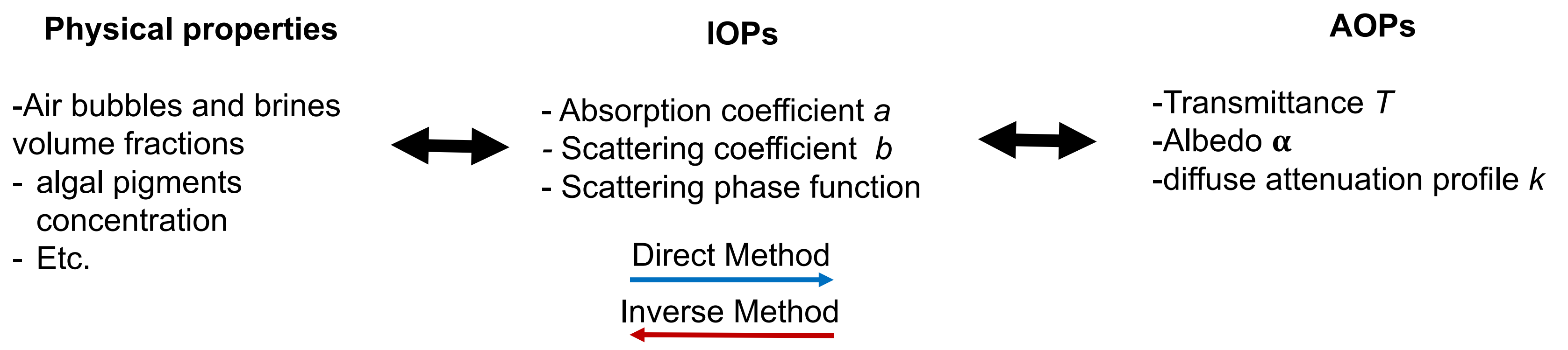
Why Study Sea Ice Inherent Optical Properties?

In situ Inherent Optical Properties (IOPs) of sea ice are powerful physical inputs that allow to directly calculate 1) the amount of light reflected, absorbed and transmitted (Apparent Optical Properties) by sea ice and 2) inferring sea ice physical properties.



Physical properties

-Air bubbles and brines volume fractions
- algal pigments concentration
- Etc.

IOPs

- Absorption coefficient *a*
- Scattering coefficient *b*
- Scattering phase function

AOPs

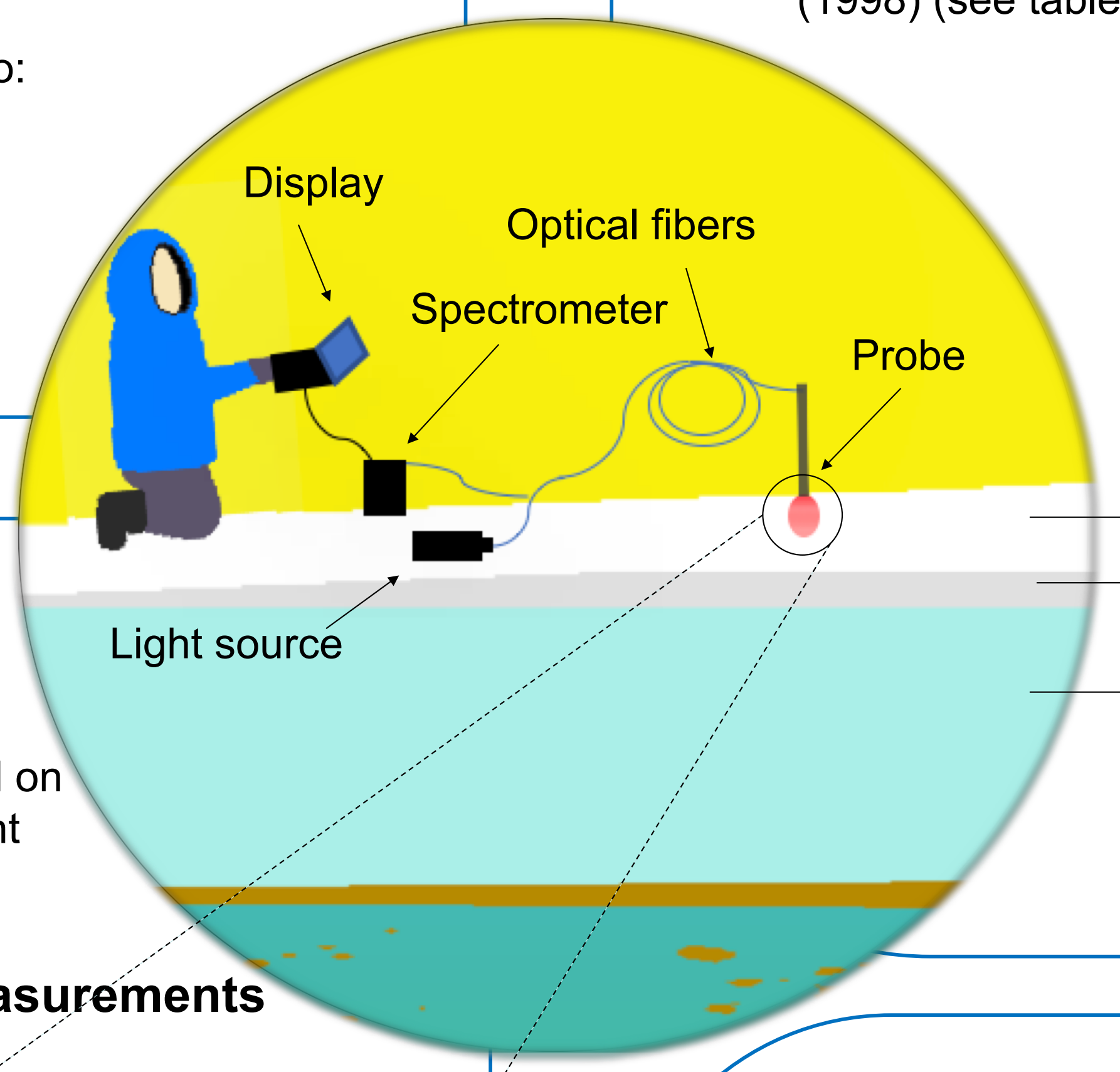
-Transmittance *T*
-Albedo **α**
-diffuse attenuation profile *k*

Direct Method

Inverse Method

Therefore, a better understanding of how sea ice IOPs evolve both in time and in space would allow to:

- **Obtain more precise sea ice energy and mass budgets.**
- **Follow more closely light availability for primary production within and under the sea ice cover.**



Diffuse Reflectance Spectroscopy

Reflectance spectroscopy is a technique where backscattered light coming out from an optical fiber is measured at different distances ρ from the source. It is currently used to diagnose human tissues based on their optical properties. Using this method to infer IOPs in sea ice rather than using larger scale apparent optical properties could help to improve our understanding of ice interaction with solar light.

Monte-Carlo Reflectance Simulations

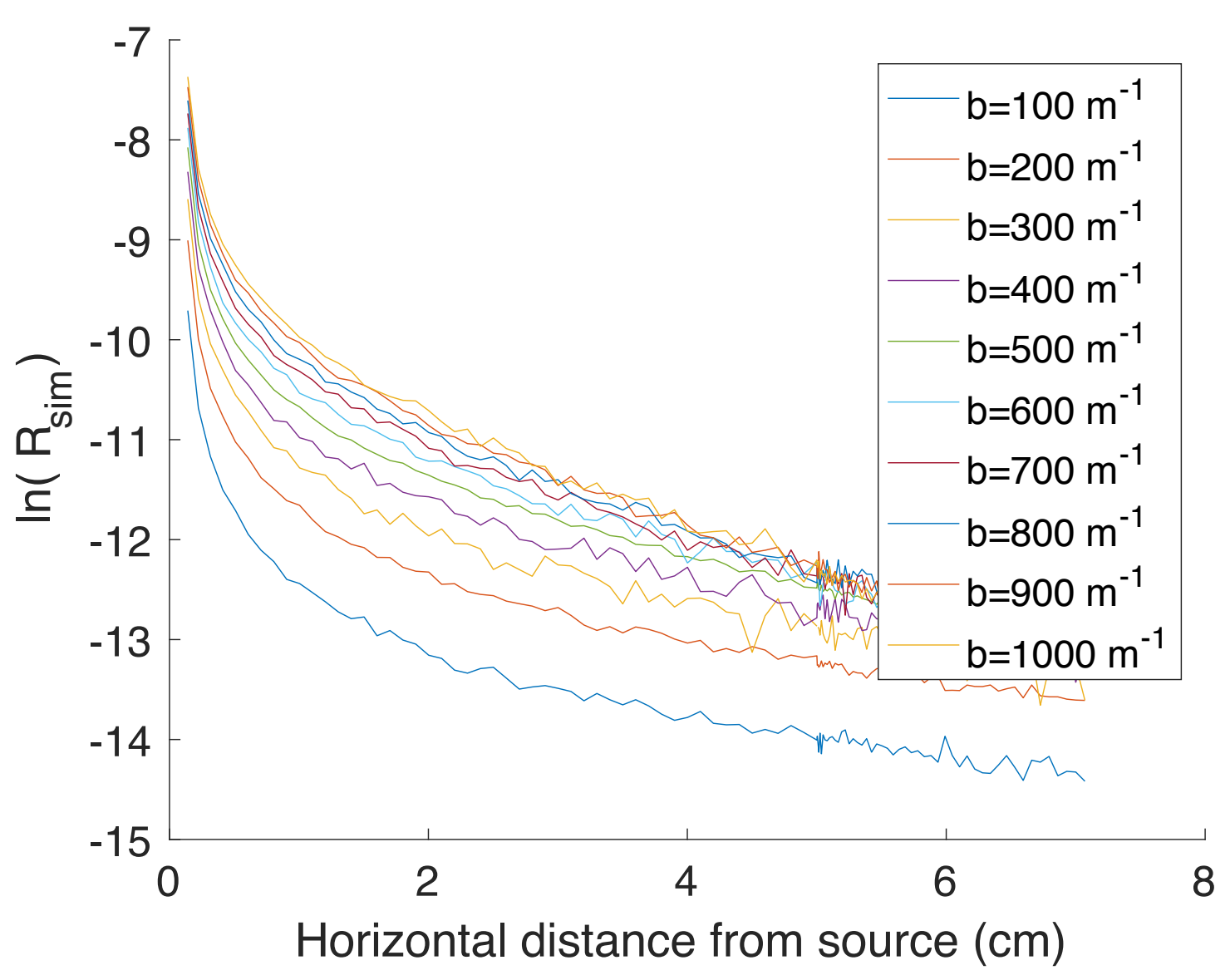


Figure 1. Simulated Reflectance vs distance from the emitting fiber for different scattering coefficients *b* (a=0.1 m^{-1} and g=0.94 (H-G)).

Comparison with an inverse method algorithm to find the best fit

leads to

Inherent Optical Properties of the Scanned Volume

Field Reflectance Measurements

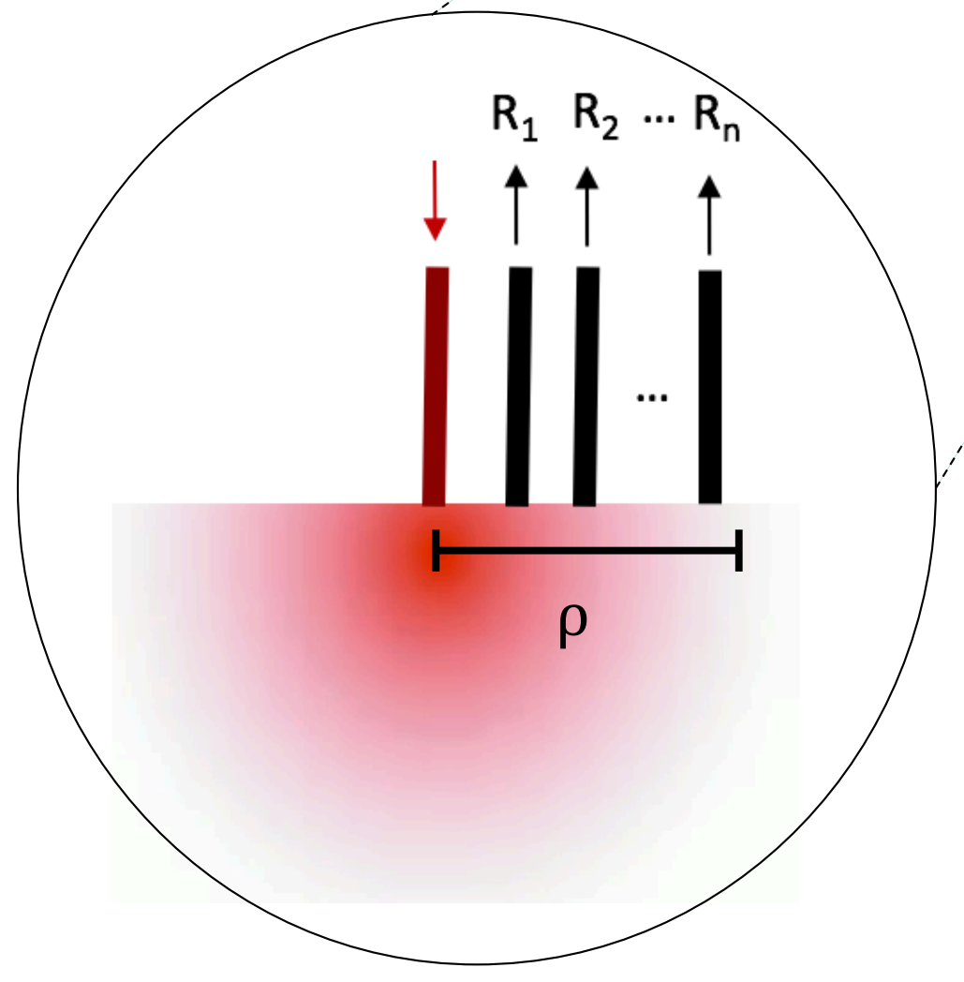


Figure 2. Conceptual scheme of a reflectance probe.

Advantages of Diffuse Reflectance for IOPs Inferring

1. Increased spatial resolution: The probe could scan a volume in the ~mm^3 to ~ cm^3 depending on the fibers geometry (distance, numerical aperture). Such a resolution is enough to determine algae or soot concentrations inside the bottommost and topmost layers.
2. In situ determination of the phase function: The phase function asymmetry parameter *g* is hard to infer *in situ* because of the highly scattering nature of ice. Reflectance geometry would allow to measure g at source-detector spacing under the scattering mean free path, providing useful information on physical properties.
3. Non-destructive: Reflectance geometry allows to measure light propagation *in situ* without digging, hence without altering ice structure.
4. More precise: Inferring IOPs to a small volume allows to have a more constrained model resulting in more precise and accurate measurements.
5. Fast processing speed: Automatized inversion allows to obtain IOPs spectra on the field within seconds to minutes. This direct feedback would allow scientists to analyze and adapt their methods to the output measurements.

What Volume Should the Probe Scan?

The size of the volume scanned by the probe is proportional to the spacing ρ between the emitting fiber and the detector. The spacing must be adapted to the physical and optical properties of the scanned medium. For the study of sea ice, the scanned volume could be in the order of the cm^3 for two reasons:

1) Brines, salts, bubbles, algae and ice crystals have size distributions ranging from less than a micron to centimeters. Therefore, the scanned volume must be in the centimeters to average the contribution of all inclusions.

2) As the source-detector distance ρ decreases, more terms N need to be included in the description of the radiance and the phase function to correctly simulate how light is backscattered. At N=2, the modified Henyey-Greenstein relation can be used to describe angular dependence of light after a scattering event:

$$p_{mHG}(\boldsymbol{\theta}) = \propto \cdot \frac{1}{4\pi} \cdot \frac{1-g^2}{(1+g^2-2g\cos\boldsymbol{\theta})^{3/2}} + (1-\propto) \cdot \frac{3}{4\pi} \cdot (\cos\boldsymbol{\theta})^2 \qquad (1)$$

Where p_{mHG} is the probability that a photon will be deviated of an angle **θ**. ∝ and *g* are 2 terms ranging from 0 to 1 that allow to describe the angular dependence of the photon. For this phase function to be valid, the source-detector spacing ρ must be bigger than 0.5/*b*(1-*g*) according to Bevilacqua (1998) (see table 1). Therefore, the scanned volume should be in the order of the cm^3 to accurately infer the IOPs of the 2 first layers.

Table 1. *Estimated Inherent optical properties and minimum spacing between source and detector to use the modified Henyey-Greenstein approximation for the different optical layers of sea ice* (Bevilacqua 1998, Ehn 2008, Light, 2008, Light 2015).

Optical layer	a(λ) (m^{-1})	b (m^{-1})	g (H-G) (-)	ρ_{min} to use mHG approximation (N=2) (cm)
Surface Scattering Layer	0.1-1	100-1000	0.85	0.33
Drained Layer	0.01-1	10-100	0.85	3.33
Interior Layer	0.01-1	1-10	0.94	83

Preliminary Monte Carlo Simulations

Using the 3D Monte Carlo method to simulate light propagation with a reflectance geometry (see figure 2), 2 preliminary tests were achieved (figure 3 and 4).

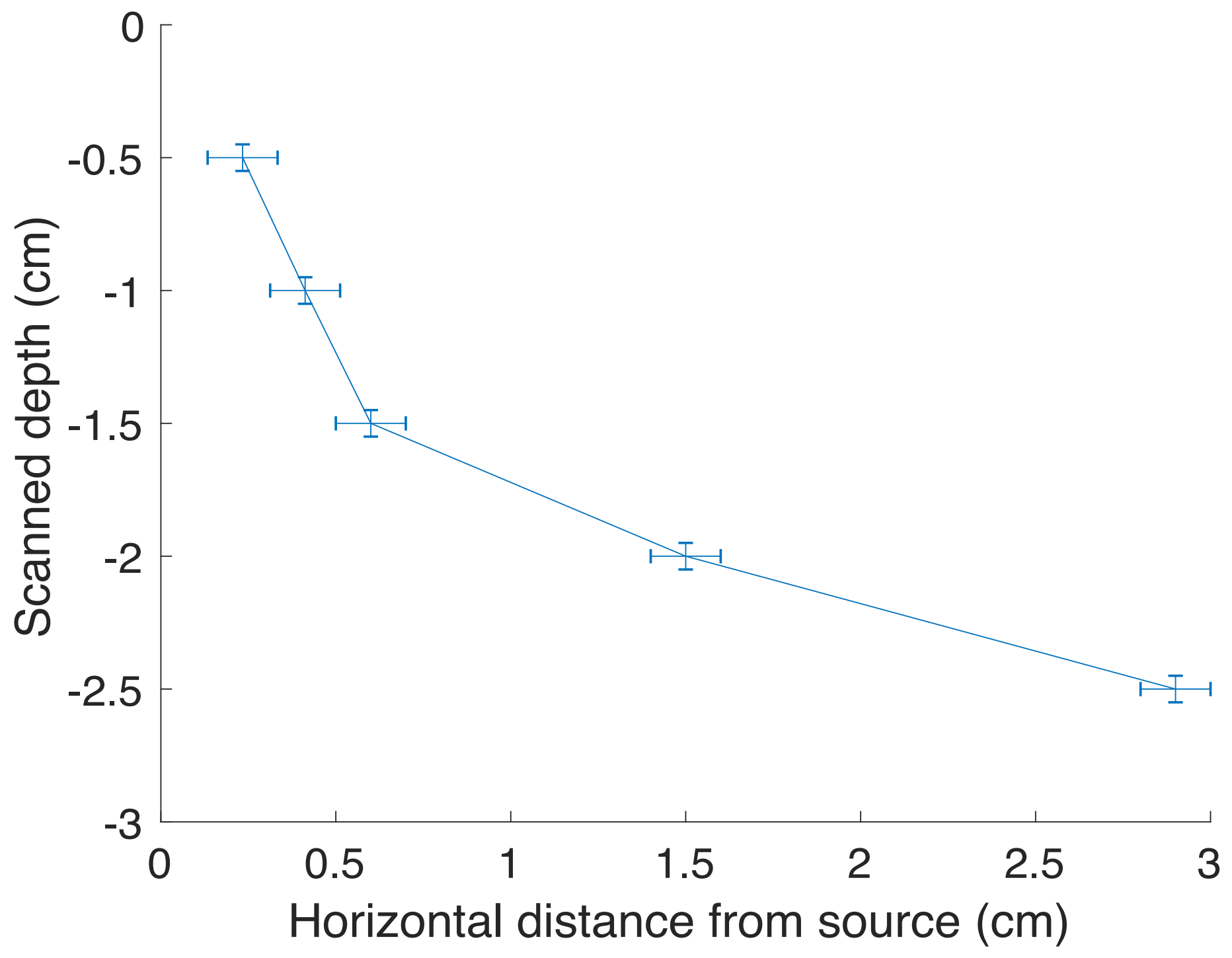


Figure 3. Depth where 95% of the detected backscattered light come from above vs distance ρ from the source (a=0.1 m^{-1}, b=100 m^{-1} and g=0.94 (HG)).

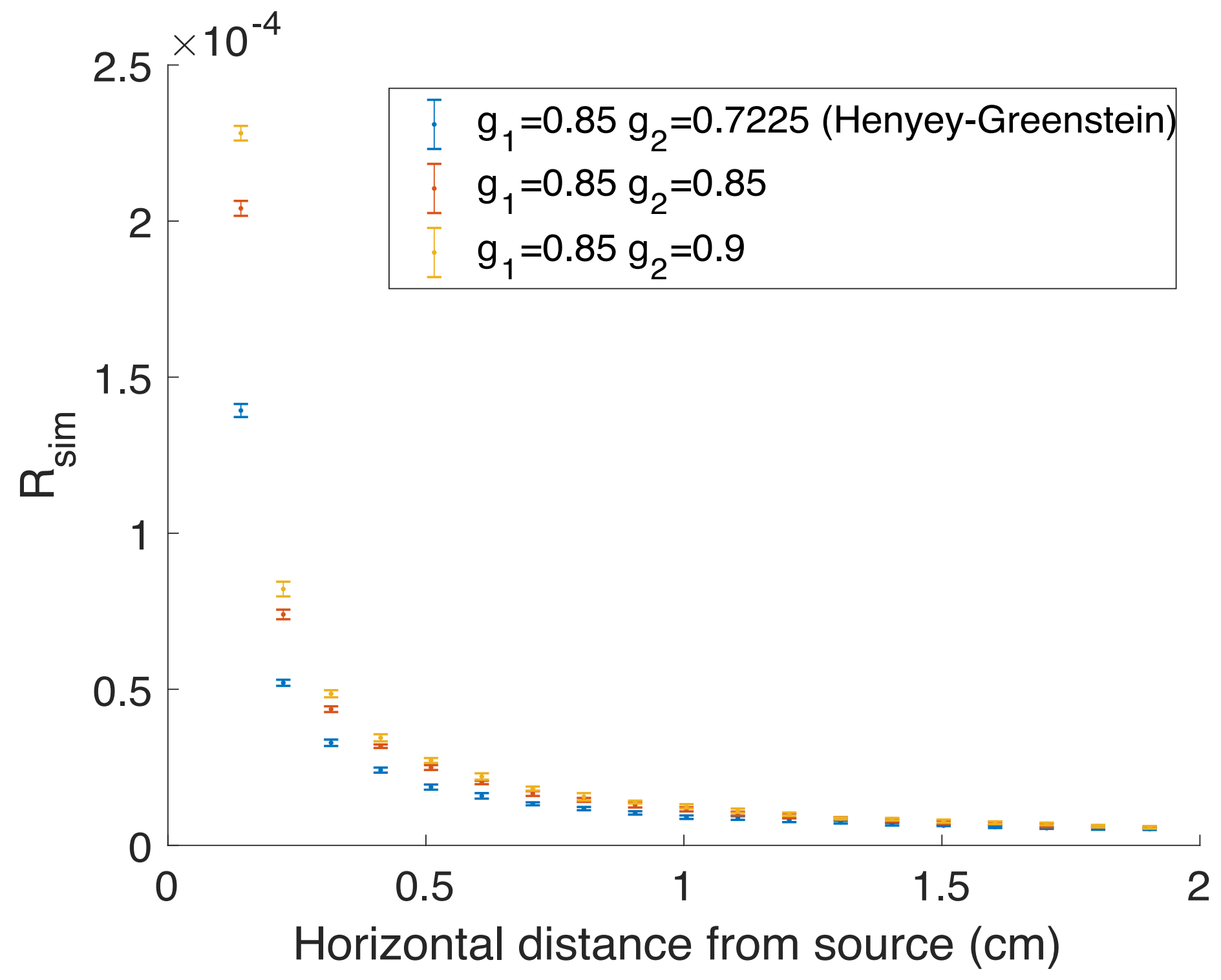


Figure 4. Simulated reflectance vs distance ρ from the source varying the second moment (N=2) of the phase function (a=0.1 m^{-1} and b=100 m^{-1}).

The scanned depth (see figure 3) allows us to know what volume size we are scanning depending on the distance ρ from the source and depending on the IOPs of the ice. The Reflectance vs distance from source relation (see figure 4) shows that, for reflectance geometry, using a 2 terms phase function (like modified Henyey-Greenstein) to describe radiance is significant when the source-detector distance is small (ρ~<1 cm).

Next Steps

-Test inversion algorithms: Determine the best algorithm to infer IOPs from field measurements.
-Simulate a look-up table: Run simulations varying the phase function asymmetry parameter, absorption and scattering coefficients. Build a 3D look-up table for the inversion.
-Design and build the probe and validate the instrument with phantoms: Build the instrument and validate its functioning using a medium similar to ice with known optical properties.
-Field tests: Test the probe with real sea ice on the field.

References: Bevilacqua, Frédéric. "Local optical characterization of biological tissues in vitro and in vivo." *Unpublished PhD diss*1781 (1998).
Ehn, J., et al. (2008). "Inference of optical properties from radiation profiles within melting landfast sea ice." Journal of Geophysical Research: Oceans **113**(C9).
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