RETRIEVAL OF HYDROSOL CHARACTERISTICS WITH MFOV RAMAN LIDAR

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1. INTRODUCTION

Nowadays, Raman lidar sounding is a conventional technique for measuring the seawater optical properties [1-5]. However, in most cases, the inversion of Raman lidar returns (retrieval of medium characteristics) employs a lidar equation in the single scattering approximation. As it was referred by many authors [6-8], multiple scattering heavily contributes to lidar returns from seawaters. Moreover, multiple scattering carries additional information, particularly, about particle size distribution, because the lidar signal is affected by forward scattering phase function. Just multiple scattering determines the angular structure of lidar return, observed with imaging or multiple-field-of-view (MFOV) lidars [9-10]. Therefore, using MFOV lidar allows one to retrieve the forward scattering characteristics.

2. FORWARD SCATTERING PHASE FUNCTION

Following to Kopelevich's model of seawater optical properties [10-12], the hydrosol phase function is determined by the two hydrosol fractions: biological (large) and mineral (small). Their ratio, namely, the ratio of their volume concentrations, β, is the only one parameter, determining the hydrosol phase function:

$$P(\lambda,\theta)=\frac{\left(b_s P_s(\theta)\left(\frac{550}{\lambda}\right)^{1.7}\beta+b_l P_l(\theta)\left(\frac{550}{\lambda}\right)^{0.3}\right)}{\left(b_s\left(\frac{550}{\lambda}\right)^{1.7}\beta+b_l\left(\frac{550}{\lambda}\right)^{0.3}\right)}, \quad (1)$$

where $P(\lambda,\theta)$ is the hydrosol phase function, λ is a wavelength (nm), θ is a scattering angle, $b_s = 1.34$ m^{-1}ppm^{-1}, $b_l = 0.312$ m^{-1}ppm^{-1}, $P_s(\theta)$ and $P_l(\theta)$ are the phase functions of small and large particles, respectively, β is the ratio of volume concentrations of small (mineral) to large (biological) particles, which is one of the most important characteristics of seawater.

As particulate phase function is strongly peaked in forward direction, the contribution of the scattering by pure water can be neglected in the small-angle region. Hence, the seawater scattering phase function at small angles is determined by only one parameter, namely, β. Kopelevich suggested [12] to use the following values for β: 0.08 for ocean water, 0.04 for hyper-productive water, and 0.6 for coastal water (influenced by dust-blown particles).

The value of β determines the weight, with which the phase functions of small and large particles ($P_s(\theta)$ and $P_l(\theta)$) appear in the resulting forward scattering phase function. The scattering properties of these particles differ strongly: their phase functions are both peaked in forward direction, but have a different angular scale, the width of a "biological peak" being about several degrees and the width of a "mineral peak" being about ten degrees.

In this work we show that measuring the angular structure of lidar return allows one to distinguish between these two peaks and retrieve the ratio of mineral-to-biological particles concentrations β.

3. ANGULAR STRUCTURE OF RAMAN LIDAR RETURN

We consider sounding of seawaters by Raman lidar. Let the initial wavelength for Raman lidar be λ_0 and the Raman-shifted wavelength be $\lambda_R = \left(1/\lambda_0 - \delta\nu\right)^{-1}$, where $\delta\nu$ is a Raman shift for liquid water (we will consider lidars, where the spectral band of the receiver is wide enough to treat all the Raman scattered light as shifted to single wavelength λ_R). The source is considered as mono-directional (with no divergence), and it lases a pulse of a short duration.

We use Cartesian coordinates (x, y, z) with the Z-axis perpendicular to the water surface and directed inward the medium. The Z-coordinate is counted from the water surface (sounding depth). Vector $\mathbf{r}(x, y)$ defines the position of the point in the plane (x, y). Vector $\mathbf{n}$ is a projection of a unit vector of the beam direction, onto the plane (x, y).

The medium is characterized by the integral and differential scattering coefficient (volume scattering function) $b(\lambda, z)$ and $b(\lambda, z, \theta)$, and the extinction coefficient $c(z)$. The phase function is defined as $P(\theta) = 4\pi\, b(\lambda, z, \theta)/b(\lambda, z)$, and the Raman backscattering coefficient is $b_R(\pi)$.

As we have shown in the previous works [13-15], the expression for spatial-angular structure of Raman lidar return could be written as:

$$F(z,\mathbf{r},\mathbf{n}) = \mathrm{W}_0 b_R(\pi)\frac{V}{2n_{ref}^2}$$
$$\times\int\exp\left(-\int_0^z\left[c_{eff}(\xi)-b_{eff}(\xi)P_{eff}^f\left(\nu(z-\xi)\right)\right]d\xi\right) \quad (2)$$
$$\times\mathrm{J}_0\left(\nu\,|\,\mathbf{r}+\mathbf{n}(z+n_{ref}H)\,|\right)\frac{\nu d\nu}{2\pi},$$

where $F(z,\mathbf{r},\mathbf{n})$ is the spatial-angular distribution of intensity of Raman lidar return at the receiver entrance, W_0 is the pulse energy, V is the speed of light in water, n_{ref} is the refractive index of water, $\mathrm{J}_k(x)$ is Bessel function of the k-th order, H is the lidar altitude, c_{eff} and b_{eff} are the effective extinction and scattering coefficients, defined as

$$c_{eff}(z) = c(\lambda_0,z)+c(\lambda_R,z),$$
$$b_{eff}(z) = b(\lambda_0,z)+b(\lambda_R,z). \quad (3)$$

$P_{eff}^f(p)$ is Hankel transform of the forward scattering phase function:

$$P_{eff}^f(p) = \frac{1}{2}\int_0^\infty P_{eff}^f(\theta)\mathrm{J}_0(p\theta)\theta\,d\theta\,, \quad (4)$$

where the effective forward scattering phase function is defined as:

$$P_{eff}^f(\theta) = \frac{b(\lambda_0,z)P^f(\lambda_0,\theta)+b(\lambda_R,z)P^f(\lambda_R,\theta)}{b(\lambda_0,z)+b(\lambda_R,z)}. \quad (5)$$

As the forward scattering phase function $P^f(\lambda,z,\theta)$ is determined by hydrosol particles, it could be found through the Eq. (1), and it depends on the parameter β only.

To get the angular dependence of lidar return $F(z,\theta)$ (the distribution of irradiance in the receiver's focal plane) one should integrate the function in Eq. (2) over the spatial coordinate:

$$F(z,\theta) = \int_0^{2\pi}\int_0^R F(z,\mathbf{r},\mathbf{n})\,r\,dr\,d\phi\,. \quad (6)$$

where R is the receiver radius.

Integrating gives:

$$F(z,\theta) = \mathrm{W}_0 b_R(\pi)\frac{V}{2n_{ref}^2}R$$
$$\times\int\exp\left(-\int_0^z\left[c_{eff}(\xi)-b_{eff}(\xi)P_{eff}^f\left(\nu(z-\xi)\right)\right]d\xi\right) \quad (7)$$
$$\times\mathrm{J}_0\left(\nu(z+n_{ref}H)\theta\right)\frac{\mathrm{J}_1(\nu R)}{\nu}d\nu.$$

The results of modeling of angular dependence of Raman lidar return are presented in Fig. 1.

The simulations were made for three typical values of β, corresponding to hyper-productive, ocean, and coastal waters. As seen from Fig. 1, the signals at small angles (of about 1 mrad) differ about ten times. Therefore, measuring Raman lidar return within different angular ranges could make it possible to retrieve β.

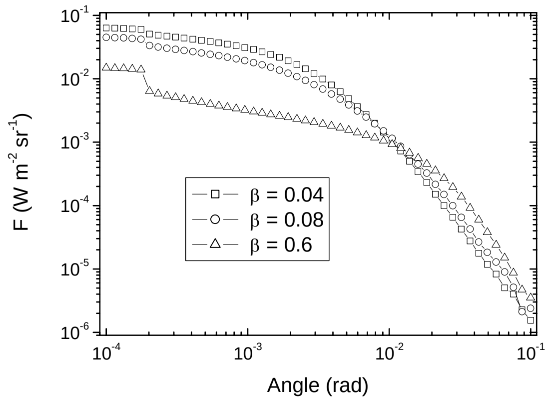

Fig. 1. Angular dependence of Raman lidar return for different values of β (0.04, 0.08, 0.6). Lidar altitude is 500 m, sounding depth is 20 m, receiver radius is 0.1 m, and extinction and scattering coefficients are 0.3 m^{-1} and 0.2 m^{-1}.

4. DEPENDENCE OF MFOV RECEIVER SIGNAL ON CONCENTRATIONS RATIO

Multiple-field-of-view (MFOV) receivers are used, e.g., retrieve the droplets size when sounding clouds [9-10]: due to multiple scattering MFOV receiver allows one to retrieve the characteristics of forward scattering.

Let F_0 and F_1 be light fluxes in the angular intervals $(0,\gamma_1)$ and (γ_1,γ_2):

$$F_0 = 2\pi\int_0^{\gamma_1}F(z,\theta)\theta d\theta, \quad F_1 = 2\pi\int_{\gamma_1}^{\gamma_2}F(z,\theta)\theta d\theta. \quad (8)$$

Then, using Eqs. (7)-(8), their ratio can be written as:

$$\frac{F_1}{F_0} = \frac{\int\frac{d\nu}{\nu^2}\mathrm{J}_1(\nu R)\mathrm{J}_1\left(\nu(z+n_{ref}H)\gamma_2\right)G(z,\nu)}{\int\frac{d\nu}{\nu^2}\mathrm{J}_1(\nu R)\mathrm{J}_1\left(\nu(z+n_{ref}H)\gamma_1\right)G(z,\nu)}-1, \quad (9)$$

where

$$G(z,\nu) = \exp\left(\int_0^z b_{eff}(\xi)P_{eff}^f\left(\nu(z-\xi)\right)d\xi\right). \quad (10)$$

This ratio F_1/F_0 is a function of two unknown seawater characteristics only: the scattering coefficient $b_{eff}(z)$ and β.

The dependence of the ratio F_1/F_0 on β is presented in Fig. 2. As seen, this ratio is quite sensitive to β, especially in the region of small values of β, where biological fraction concentration is of particular interest. Therefore, if the scattering profile is known, β can be easily retrieved.

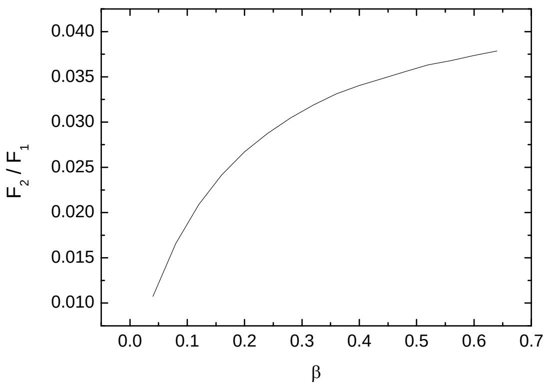

Fig. 2. The dependence of ratio F_2/F_1 on β for $\gamma_0 = 1$ mrad and $\gamma_1 = 20$ mrad (half-angles). The other lidar and seawater parameters are the same as in Fig.1.

In order to retrieve the scattering profile, the depth dependence of Raman lidar waveform, elastic lidar waveform, or their combination could be used. For example, in Ref. [15] the retrieval of scattering profile from elastic lidar waveform is based on the iterative scheme, in which multiple scattering is considered. To include multiple scattering into the iterative scheme, one needs to know the forward scattering phase function. Hence, measuring Raman lidar return with MFOV receiver can be included as a step into the iterative scheme to obtain β. At each step, the scattering profile obtained is used to calculate β through the ratio F_2/F_1; the value of β is used to calculate forward scattering phase function; calculated phase function is used for the next step of iteration to obtain scattering profile, and so on. The scheme [15] was based on the fact that lidar return is not very sensitive to exact form of forward scattering phase function, and a typical phase function for the appropriate water case was used. Additional knowledge of β can improve the accuracy of the method.

5. CONCLUSION

In this work, the possibility to retrieve the ratio of volume concentrations of small to large particles with the MFOV Raman lidar is demonstrated. This ratio, β, is one of the most important characteristics of seawater, e.g., it is the main factor, determining forward scattering phase function. Knowledge of the value of β can be useful in retrieval of other parameters of seawater, such as extinction and scattering profiles, because it allows one to know the forward scattering phase function, which is necessary in multiple scattering simulation.

Using Raman scattering has an advantage over the elastic scattering, because one does not need to know the elastic backscattering phase function, which is the most indefinite factor in lidar sounding of seawater.

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