HYDROBETA: A NEW INSTRUMENT FOR MEASURING *IN-SITU* PROFILES OF THE VOLUME SCATTERING FUNCTION FROM 10 TO 170 DEGREES

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INTRODUCTION

HydroBeta measures the optical volume scattering function (VSF) of natural waters. The VSF is an inherent optical property that is fundamental to understanding and modeling radiative transfer in oceans or lakes. Yet it has seldom been measured *in situ.* Most researchers still base their analyses on a relatively small data set taken over 25 years ago.[1]

DEFINITION OF THE VSF

The volume scattering function, $\beta(\psi)$ is defined in terms of a collimated beam illuminating a small volume of water. Scattering causes a fraction of the incident flux to be diverted away from the incident beam at various angles. In general the amount of scattering varies greatly with angle. In most cases the scattering is concentrated in the near-forward angles, though significant scattering occurs at all angles. Mathematically, the VSF is defined as the second partial derivative of the scattered flux, Φ, with respect to solid angle Ω and scattering volume V, normalized by the incident, collimated irradiance E, *viz.*,

$$\beta(\psi) = \frac{\partial^2 \Phi(\psi)}{E\,\partial\Omega\,\partial V},$$

where ψ is the scattering angle with respect to the collimation axis of the incident irradiance. Although not shown explicitly, $\beta(\psi)$ is also a function of wavelength λ.

APPROACH

HydroBeta projects a well-collimated beam of light through the water, and uses narrow-angle radiometers to measure the radiance emerging at various angles from a portion of the beam. The measurement volume is defined by the intersection of the beam with the field of view (FOV) of the receiver. Unlike earlier “free-angle” designs, which used a single movable receiver to measure at all angles, HydroBeta uses an array of stationary receivers, viewing a common volume, to measure at discrete angles. This approach greatly speeds the measurement of the VSF, while improving the stability of the calibration. It also allows the receivers to be tailored somewhat to the dramatically different signal levels found at different angles. The exact angles, however, are not fixed into the design of the instrument, so that the user can select which specific angles to measure. The source and receivers are arranged so that the surfaces of their windows define a circle of 30 cm diameter.

One of HydroBeta's key features is that it provides for calibration based on radiometric standards. Its calibration does not depend on a standard scattering medium, pure water, or calculations of its sample volumes.

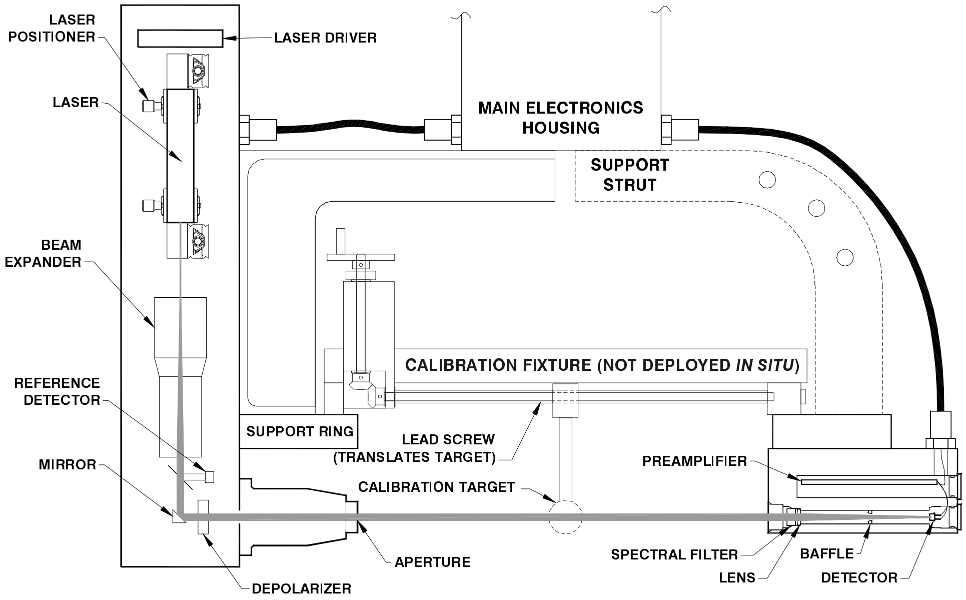

Figure 1: Cross-Section View

LIGHT SOURCE

HydroBeta uses a diode-pumped solid-state laser to generate a collimated beam of light with a wavelength of 532 nm. The laser is modulated at about 1 kHz, and the receivers are synchronized to the modulating signal to distinguish between scattered light and solar background. The laser's peak power output is about 5 mW.

The laser is mounted on a set of miniature positioning stages so its alignment can be precisely adjusted. The beam emerging from the laser is about 1.2 mm in diameter, and passes through a beam expander that enlarges it by a factor of 6. The expander also reduces the beam divergence by the same factor, producing a final divergence less than 0.05 degree. After expansion, the beam passes through a beam splitter that directs a small portion of the beam to a reference detector. The reference detector output is used to normalize the measured signals, compensating for variation in the laser's output. The beam is then reflected into the plane of the receivers by a right-angle mirror.

Because scattering is sensitive to polarization, the beam is directed through a depolarizer. While it does not truly depolarize the light, in the sense of making it completely incoherent, it does "scramble" the beam such that it includes a continuous range of polarization states, evenly distributed throughout the beam cross-section.

Finally the beam passes through baffles that reduce it to its final diameter of 5 mm. The baffling tube and apertures are carefully designed to minimize extraneous reflections.

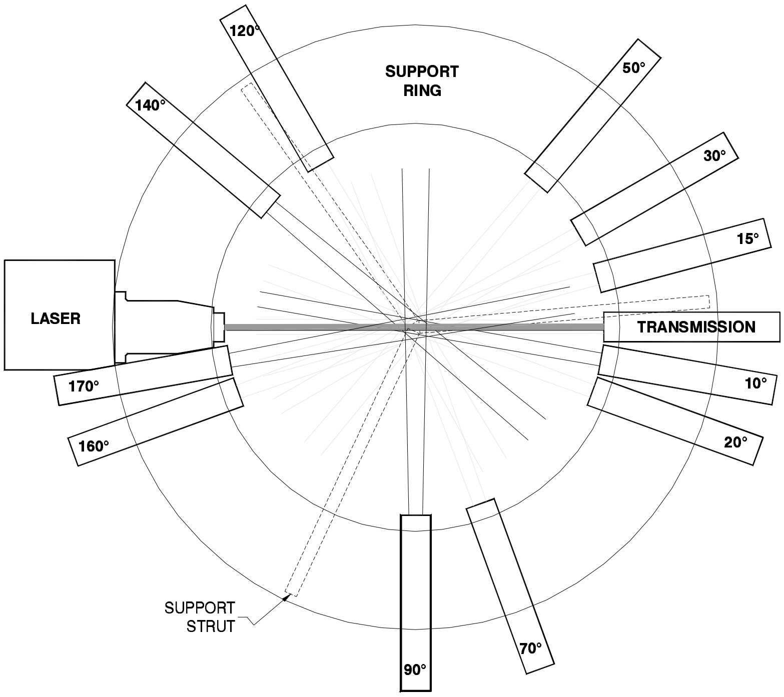

Figure 2: Top View Showing Receiver Fields of View

RECEIVERS

HydroBeta includes 12 receivers for simultaneously measuring beam transmission and scattering at 11 discrete angles. Each receiver has an interference filter to reduce solar background, a lens with a 10 cm focal length, and one or more internal baffles to reduce its response to extraneous light. The open aperture of each receiver is 1 cm.

Because the amount of scattering varies drastically depending on angle, the size of detector used in each receiver is set according to the angular range it is intended to measure. The detectors range in diameter from 0.8 mm to 5 mm. The smallest detectors are used at forward angles, where the scattering signals are relatively large and angular selectivity is most important. The 0.8 mm detector provides a field of view half-angle of 0.2 degree. The largest detectors are needed for scattering angles greater than 70 degrees, where the signals are extremely small and angular selectivity is not as important. The maximum field of view for the backscattering receivers is 1.2 degrees (half-angle).

The preamplifier electronics in the receivers have discrete, electronically-controlled gain settings. These are used to adapt to different scattering levels, and to reduce the gain for calibration purposes.

Figure 3: Photograph of HydroBeta

CALIBRATION

HydroBeta is calibrated using procedures similar to those used for our single-angle backscattering sensors, and described in detail in an earlier paper.[2] Briefly, each receiver's response is characterized by moving a diffusing target throughout the volume of intersection between the receiver field of view and the laser beam. This yields a weighting function, $W(z,c)$, that describes the response at each distance z along the axis of motion of the target. W is also a function of c, the beam attenuation coefficient, because attenuation by the water affects how rapidly the response falls off as a function of distance. However, once $W(z,c)$ has been measured in water with a known c, it can be accurately calculated with other values of c.

The mathematical model presented in Ref. 2 rigorously relates $W(z,c)$, as measured by the calibration procedure, to the absolute response in a diffuse scattering medium as follows:

$$\beta(\psi^*) = sg\rho \frac{\int_0^\infty W(z;c_w)}{\int_0^\infty W(z;c)}$$

where s is the output signal of the sensor. g is a constant that incorporates several geometric and electronic factors, all of which are readily measurable or can be calculated from basic geometry. The complicated functions that describe the sample volume, imperfections in the optics, and so on, need not be calculated because their effects are all incorporated in the measurement of W. c is the beam attenuation at the time of the measurement (measured by HydroBeta's "0-degree" receiver), while c_w is that of the water in which the instrument was calibrated.

The angle of the measurement is denoted Ψ^* to signify the fact that an individual receiver is actually sensitive to a (small) range of angles. In HydroBeta the range of angles for each receiver is quite small (between ±0.2° and ±1.1° depending on the angle of measurement).

Finally, ρ is the diffuse reflectivity of the calibration target. This may have to be interpreted differently for some angles, as noted below.

For angles from about 60 to 170 degrees we use a Spectralon target whose reflectivity is known to be 99% and closely approximates an ideal cosine angular distribution. The target may be rotated to accommodate different portions of the angular range, as shown at right. The axis of motion of the target can also be rotated about the center of the ring.

For angles less than about 50 degrees, we use a transmitting diffusing target. In this case the constant ρ in the formula above must be replaced by a factor characterizing the diffuse transmission of the target. HydroBeta can also be used as a platform for measuring the angular response of the diffuser, by moving a single receiver to various positions around the ring while viewing the stationary target.

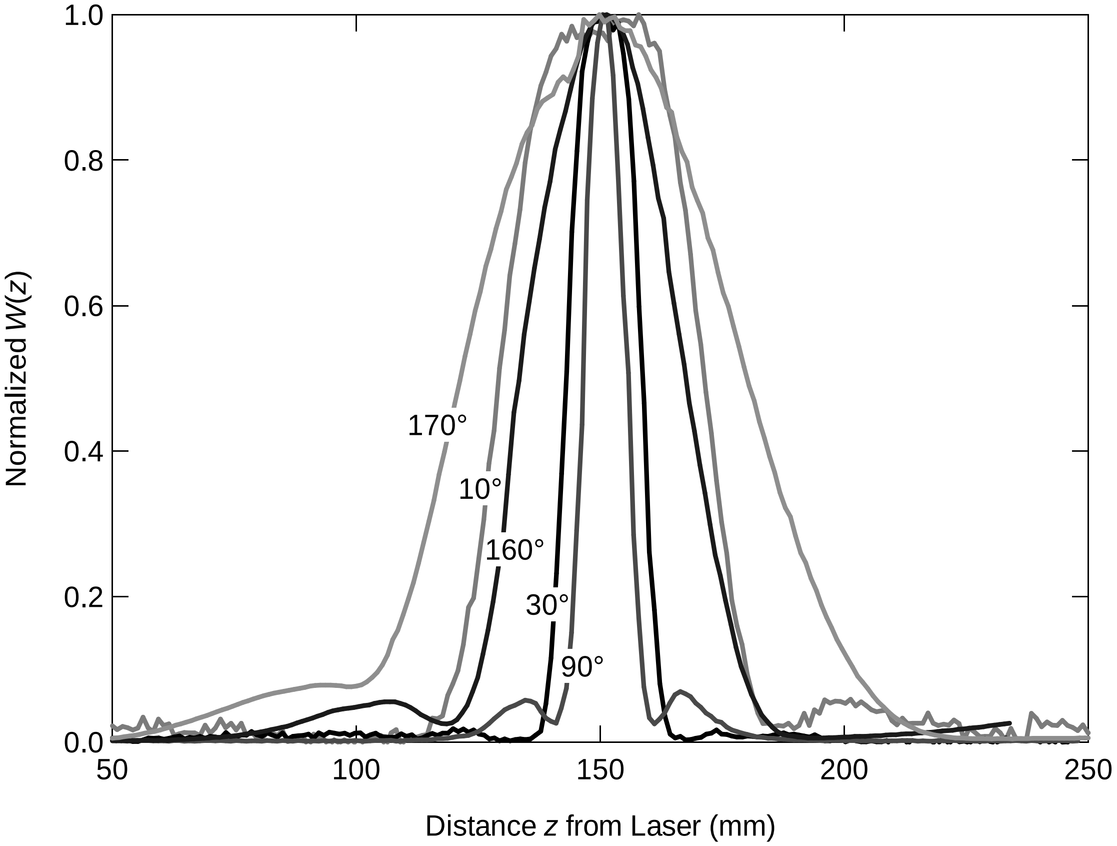

Figure 4: Typical Measured Calibration Curves

CONCLUSIONS

HydroBeta provides a much-needed capability for measuring VSF profiles in natural waters, with numerous improvements over previous instruments. Our oral presentation will include data that demonstrate its capabilities *in-situ*.

ACKNOWLEDGEMENTS

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REFERENCES

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