Hyperspectral Optical Properties, Remote Sensing, and Underwater Visibility

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LONG-TERM GOALS

Our overall goal is to advance our understanding of the utility of hyperspectral and high-spatial resolution remote-sensing imagery for estimating water-column optical properties, bathymetry, and underwater visibility.

OBJECTIVES

Our major objectives are to investigate two problems related to the interpretation of hyperspectral remote-sensing imagery: 1) estimating underwater visibility and associated optical parameters from remote sensing data, and 2) quantifying the effects of resuspended sediments in optically shallow waters on remote sensing data and algorithms for predicting bottom depth and water optical properties.

APPROACH

Optically shallow waters are by nature highly dynamic environments that experience a variety of processes which alter their optical properties. For the application of hyperspectral remote sensing of optically shallow waters, it is important to understand the effects some of these processes have on the optical properties of the bottom boundary layer. Waves and tides, for example, resuspend sediments in varying degrees depending on topology, sediment characteristics, and the strength of the forcing mechanism. To a hyperspectral imager, the apparent reflectance of the bottom will change dramatically depending on these bottom boundary conditions. Although the interactions of waves and tides with bottom sediments have been studied and modeled, their effects on the bottom boundary-layer optical properties and hence on the remote-sensing reflectance has rarely, if ever, been systematically studied. As pointed out by Philpot [1989] and Maritorena et al. [1994], bathymetric mapping with passive multispectral imagery is a non-unique modeling problem. That is, for example, the same RSR can result from two different bottom depths if the bottom albedos differ accordingly. Similarly, an apparent change in the bottom albedo caused by a nepheloid layer will result in errors in bottom depth estimation from the RSR. However, these errors can be anticipated, and possibly corrected, if adequate information of resuspension events in the target area can be obtained and fed into an appropriate optical model.

To conduct measurements of the hyperspectral light field in situ, we developed a new hyperspectral radiometer system called HydroRad that is designed to measure both bottom and surface spectral irradiance (and radiance) simultaneously. From these measurements the bottom spectral irradiance

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14. ABSTRACT
Our overall goal is to advance our understanding of the utility of hyperspectral and high-spatial resolution remote-sensing imagery for estimating water-column optical properties, bathymetry, and underwater visibility.

15. SUBJECT TERMS

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reflectance and surface remote-sensing reflectance are obtained. In addition to the time-series measurements of the bottom-boundary-layer optical properties, we perform extensive IOP and AOP measurements of the water-column optical properties since these measurements will be needed to develop and test our shallow-water optical models. During ship deployments, we also collect water samples for analysis of particle size distributions, dry weight and composition. These measurements will be important for understanding and modeling the optical properties and optical effects of resuspended sediments and associated optically-active matter, which is still very poorly understood.

Optical modeling will consist of four major components: 1) developing optical-property models for resuspended sediments and associated optically-active matter, 2) forward numerical modeling for solving the radiative transfer equation, 3) developing empirically-based coupled hydrodynamic-optical models for bottom-boundary layer effects, and 4) developing semi-analytical models for remote sensing of optically shallow waters that includes the optical effects of the bottom boundary layer and suspended sediments in the water column. Modeling component (1) is straightforward and simply requires the appropriate data which we will collect on this program. Component (2) is easily achieved with Hydrolight, which the author has many years of experience using. Achieving component (3) will rely heavily on the quantity and quality of the mooring data and it is recognized that these models may be regional and require statistical tuning parameters. Modeling component (4) is also likely to be regional to some degree and its general applicability will no doubt depend on how comprehensive a data set we collect on HyCODE.

WORK COMPLETED

Our field work was directed by ONR to focus on the West Florida Shelf study site, where we were directed to install self-contained optical instruments at two moorings maintained by the University of South Florida (Dr. Robert Weisberg). For this effort we built several a-beta, c-beta, HydroScat-2 and HydroRad instruments, which all contained their own internal batteries and controller/data loggers. Because we could only service these moorings every two months or longer, we also developed external battery packs to extend the time the instruments could operate. We first began deployment of these instruments in December 1999, and maintained instruments at two mooring sites until August 2001. In addition to conducting mooring service cruises about every two months, over this period we also conducted two major research cruises in conjunction with USF.

After the first few mooring service cruises, it became apparent that two-month turnaround times were too long for the conditions. The main problem was biofouling, which usually made optical measurements useless after about two weeks. Figure 1 shows an example photograph of one of our instruments, the c-beta, after recovery on a bottom mooring that was deployed for two months. As one can see, fouling was quite a severe problem in this environment. Budget constraints would not allow servicing cruises at a higher frequency than every two months, so we developed new types of anti-fouling methods. Figure 2 shows a photograph of a c-beta prepared for deployment where we wrapped the attenuation tube of the instrument with copper screening. Another type of antifouling technology we developed for the backscattering sensors HdyroRad radiometers was copper shutters that could cover the light collectors and open automatically during sampling. Figure 3 is a photograph of a HydroScat-2 outfitted with a mechanical copper shutter. Figure 4 is a photograph of a HydroRad light collector with a similar type of copper shutter that we developed on this project.

We have also developed a novel remote sensing algorithm to relate remote sensing reflectance to underwater visibility. We are currently in the process of verifying the model with radiative transfer solutions and with in situ measurements we have been collecting on another program. Another problem being addressed on HyCODE is the effect of bubbles on remote sensing reflectance. Because we have the capability of measuring the volume scattering function of bubbles, as well as their effect on water leaving radiance, we have been conducting experiments and making measurements of these effects, both in the laboratory and on cruises. The extensive mooring data we collected in the WFS has been processed and we developed pages on our website (www.hobilabs.com) to allow users to graphically display these results.

RESULTS

An example of a time series of spectral backscattering and chlorophyll fluorescence as measured by a HydroScat-2 on a benthic mooring in the WFS is shown in Figure 5. This was the most challenging environment to work in and we generally could obtain a time series for no longer than seven to 10 days. Nonetheless, these time series revealed significant temporal variability as revealed by the graph in Figure 5. Moreover, these data show that chlorophyll fluorescence did not consistently correlate with backscattering or other optical properties, indicating the complicated relationship between fluorescence and optical properties in this environment. Figure 6 shows a time series of the remote sensing reflectance as determined by HydroRad measurements at another WFS surface mooring. These data could be obtained for much longer time periods and also reveal the temporal variability in RSR at this site. These results are being studied to determine if the variations in the optical properties are correlated with the Eckman transport as determined by Dr. Robert Weisberg using the physical data collected on these moorings.

To develop models of the effects of resuspended sediments on the propagation of light and remote sensing, it is necessary to determine the relationships of the concentration of these suspended sediments to their inherent optical properties. Although these measurements were unfortunately not conducted in a systematic manner on HyCODE, we have conducted this type of study on other programs and are applying it to our work on HyCODE. For example, Figure 7 shows measurements of the total scattering coefficient vs. their corresponding total suspended sediment concentrations (TSS). The slope of the linear regression provides the direct relationship between these properties. By determining the slopes across the spectrum, a plot of the slopes vs. wavelength can be determined, as shown in Figure 8. Another regression of the slopes vs. wavelength provides a model equation that gives the spectral relationship of suspended sediments to their IOP's. We are using these relationships in our optical models to relate suspended sediment concentrations to light attenuation and remote sensing, and ultimately the effects on underwater visibility.

To develop methods for estimating underwater visibility from remote sensing, we have derived an exact relationship between the water optical properties and the water leaving radiance. To our knowledge, this is the first exact equation relating remote sensing to water optical properties that expresses the complete set of variables and their relationships. The equation can be expressed as

$$L_w(\theta_L) = E_d^s \frac{\beta(\psi)}{qK_L^s} + L_p \qquad (1)$$

where θ_L is the sensor look angle relative to the zenith, E_d^s is the incident irradiance due to the sun (sans sky), β is the volume scattering function at the scattering angle ψ specified by the intersecting angle of the sun and looking angles, K_L^s is the irradiance attenuation coefficient for the propagation of direct sunlight, and L_p is the path radiance due to skylight (sans sun) that adds to the water leaving radiance L_w. The geometric quantity q is give by $1/\cos\theta_s + 1/\cos\theta_L$, where θ_s is the sun angle. It is easy to show that L_p will always be insignificant compared with the first term in Eq. 1 and can safely be ignored. We are currently investigating the import of this exciting result and how it can be usefully applied to remote sensing and underwater visibility problems (Maffione, 2002).

As previously noted, we have also been investigating the effects of bubbles on optical propagation and remote sensing. One aspect of the problem we are trying to address is to see if naturally suspended bubble distributions in the surface layer can be definitely detected optically. Because bubbles produce a VSF that is radically different than the VSF of marine particles, it should be possible to detect the effects of bubbles on the VSF in situ. To first test this method, we have conducted laboratory measurements of bubble populations to ensure that we can distinguish their VSF from suspended particles. Figure 9 shows the measured VSF of bubbles generated in the lab compared with calculations of their VSF from Mie theory, clearly illustrating our ability to measure bubble VSF's with the HydroBeta. We are currently analyzing data from recent cruises to see if we can detect these effects in the ocean, where we simultaneously measured water leaving radiance.

IMPACT/APPLICATIONS

Our long-term observations of optical properties in the west Florida shelf, continuously from moorings and synoptically from regular cruises, we further our understanding of optical variability in this type of coastal environment. This will allow us to develop and test predictive models of optical properties based on coupled circulation, productivity, and bio-optical models. Our parallel research on the relationship between underwater visibility and beam propagation parameters to remote-sensing reflectance will then allow us to estimate optical system performance based on remote-sensing imagery.

TRANSITIONS

The instruments and methods for long-term optical mooring that we have developed for this project are being used by HyCODE colleagues working at the LEO 15 site. They are also being used on a NOPP effort being conducted in the Monterey Bay area by the Monterey Bay Aquarium Research Institute, the Naval Postgraduate School, HOBI Labs, and others.

RELATED PROJECTS

I am working closely with investigators at USF (Carder, Weisberg, Walsh) to instrument an array of mooring sites in the west Florida shelf and collaborate on integrating the measurements into a coupled model being developed for this region. This project is also related to our research on light scattering funded by ONR (Investigation of Light Scattering by Ocean Waters).

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Figure 1. Photograph of a c-beta instrument after two months at one of the mooring sites.

Figure 2. One attempt to mitigate the biofouling by enclosing the attenuation tube of the a-beta and c-beta with copper screening.

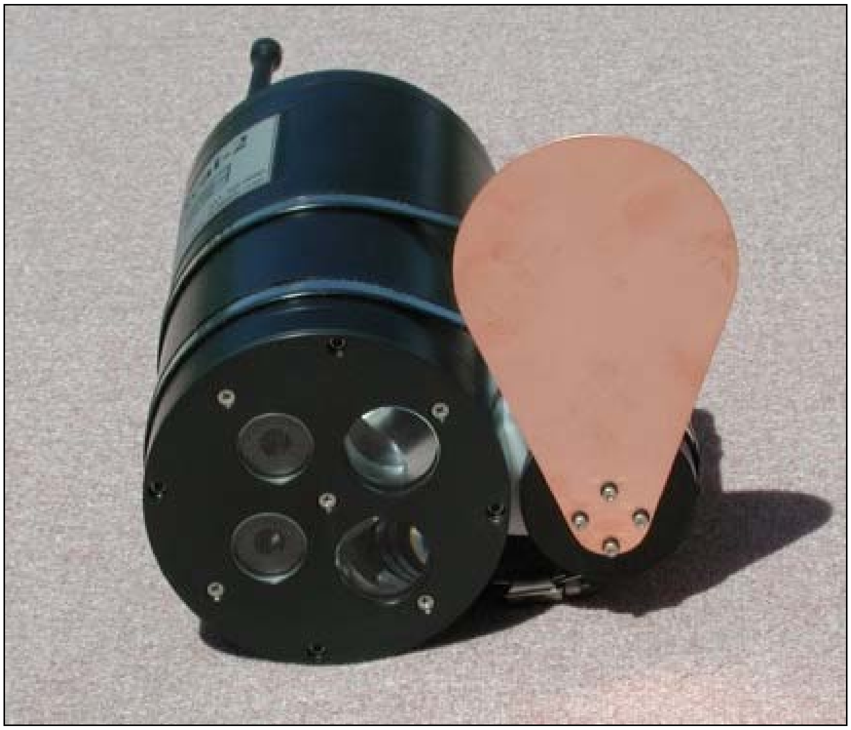

Figure 3. HydroScat-2 with new HydroShutter. The HydroShutter covers the optics of the HydroScat-2 with a copper plate to prevent bio-fouling. During sampling, the plate is rotated out of the way of the optics. Long-term mooring deployments have demonstrated that this technology keeps the optics free of fouling for over three months in highly fouling environments.

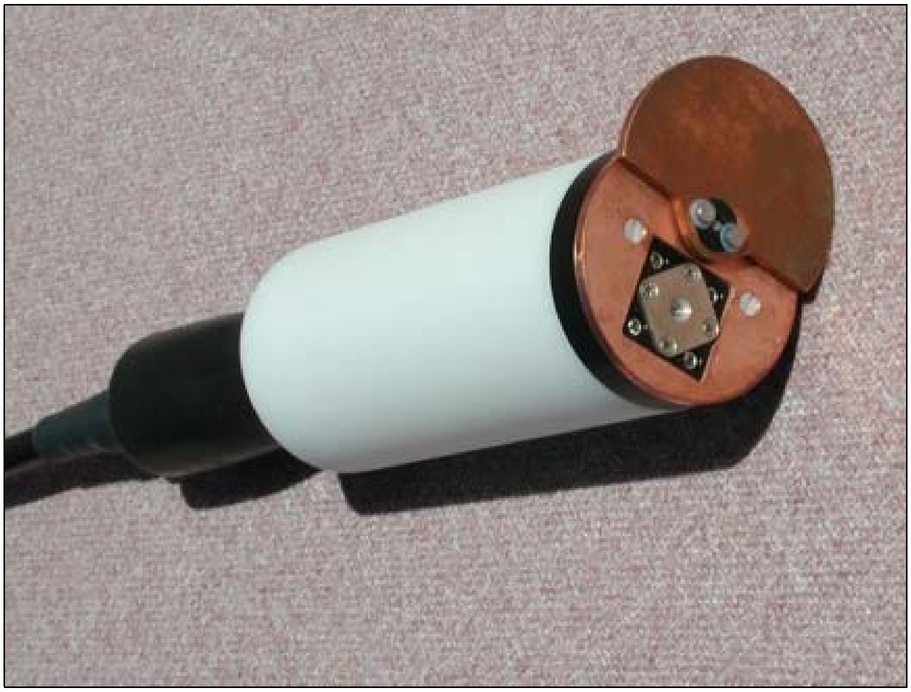

Figure 4. HydroRad fiber-optic light collector with new integrated HydroShutter. The HydroShutter covers the optics of the light collector with a copper plate to prevent bio-fouling. During sampling, the plate is rotated out of the way of the optics. Long-term mooring deployments have demonstrated that this technology keeps the optics free of fouling for over three months in highly fouling environments.

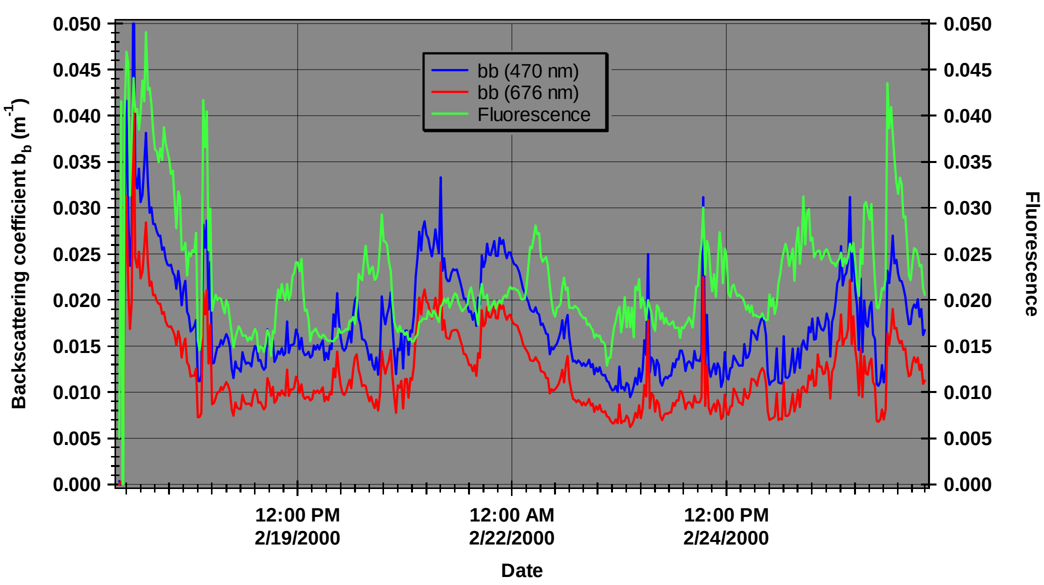

Figure 5. Time series graph of backscattering and chlorophyll fluorescence take with a HydroScat-2 on a benthic mooring in the WFS. The chlorophyll fluorescence sometimes correlates with backscattering and other times does not, illustrating the complicated nature of chlorophyll fluorescence and its relationship to benthic water optical properties.

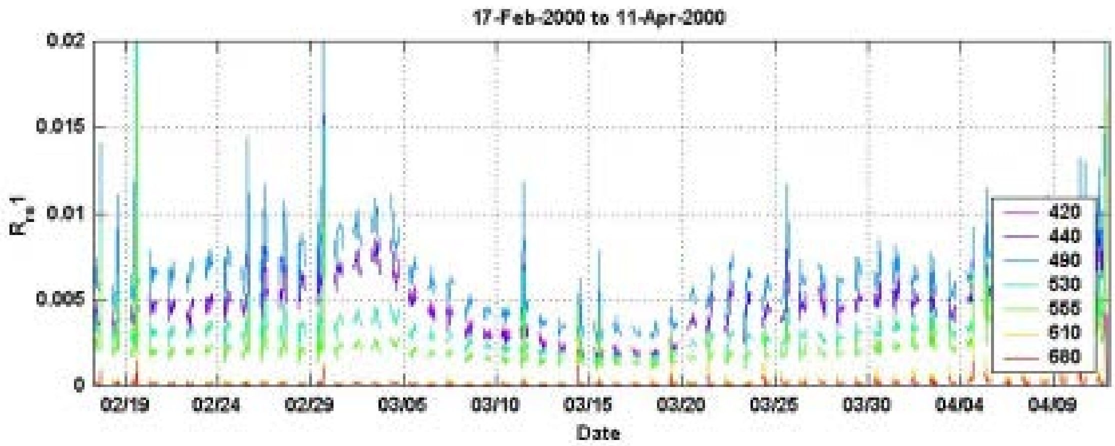

Figure 6. Time series of the remote sensing reflectance as determined by HydroRad measurements at one of the WFS moorings (EC3).

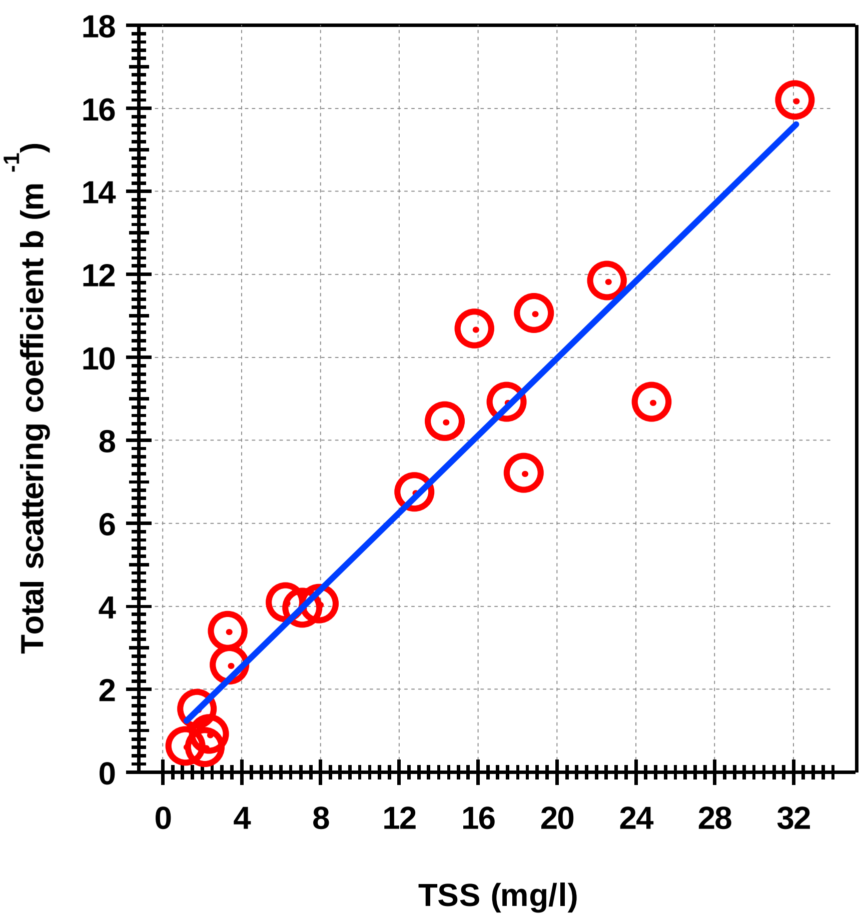

Figure 7. Measurements of the total scattering coefficient (532 nm) vs. total suspended solids (TSS) concentration. Circles are measurements and the solid line is a linear regression to the data.

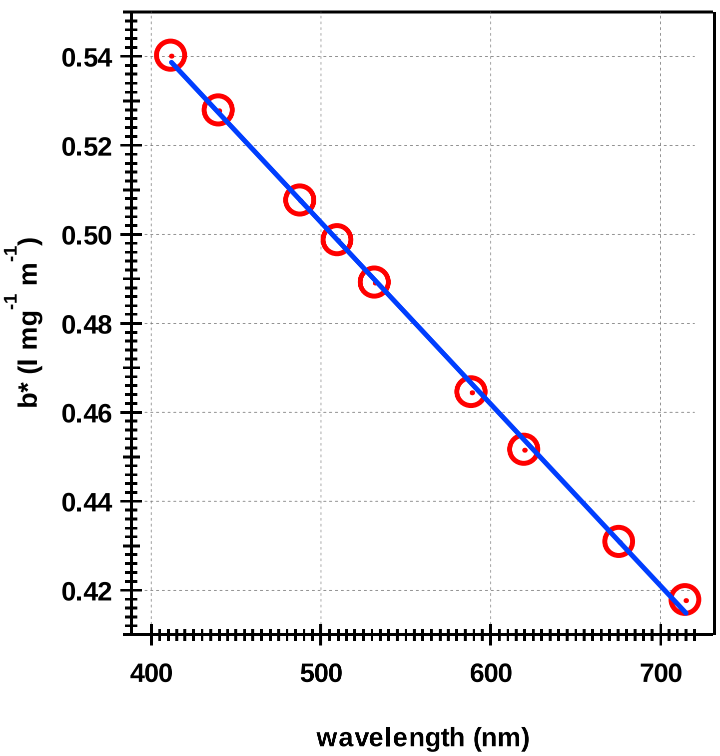

Figure 8. Slopes of b vs. TSS, as determined in Figure 7, as a function of wavelength. Circles are empirical determinations and the line is a linear regression to the data.

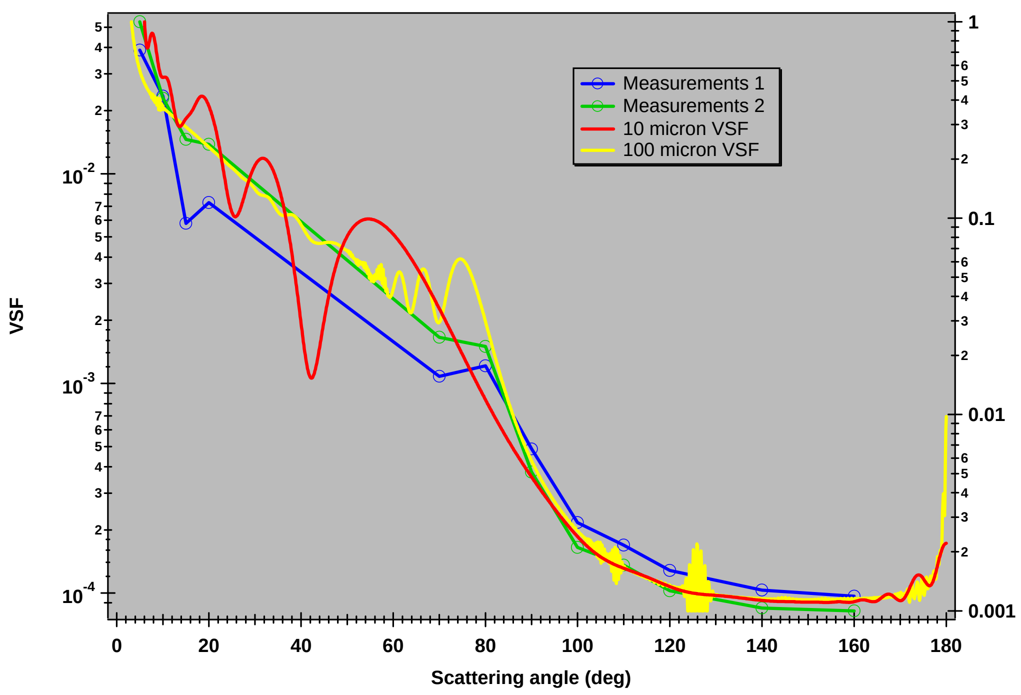

Figure 9. Measurements of the VSF of bubbles made with the HydroBeta compared with Mie theory calculations.