Intercomparison of spectral backscattering coefficients measured in-situ using several Hydroscat instruments – Results from PlymCal-2 and REVAMP cruises.

Jørgensen, P.V.1), Tilstone, G. 2), Høkedal, J. 3) & Schönfeld, W. 4)

1) *Danish Meteorological Institute, Lyngbyvej 100, DK-2100 Copenhagen O, DENMARK, pvj@dmi.dk*
2) *Plymouth Marine Laboratory, Prospect Place, The Hoe, PL1 3DH Plymouth, ENGLAND, ghti@pm.ac.uk*
3) *Norwegian Institute for Water Research, Brekkeveien 19, 0411 Oslo, NORWAY, jo.hoekedal@niva.no*
4) *Institute for Coastal Research, GKSS Research Center, Max Planck Strasse, D-21502 Geesthacht, GERMANY, wolfgang.schoenfeld@gkss.de*

1. ABSTRACT

Two large inter-calibration workshops (PlymCal-1 & 2) were conducted at Plymouth Marine Laboratory (PML) as part of the MERIS calibration/validation work within ESA's MAVT (MERIS & AATSR Validation Team) group in 2001 and 2002. In this paper the results from PlymCal 2 are presented as well as measurements from two cruises made within the framework of the REVAMP project funded by the EU.. Four institutes participated in PlymCal 2 when different versions of the Hydroscat backscattering instrument were inter-compared. Two of the instruments measured the backscattering coefficient (bb) at six different wavelengths, one at 4 wavelengths and one at two wavelengths. During PlymCal-2 measurements were made at sea, in both Case 1 and Case 2 waters and in the laboratory in tank experiments. The results were encouraging. In particular, the PML and GKSS instruments compared favourably. The NIVA and DMI instruments were slightly higher, but in good agreement with the other instruments in the blue and green regions of the spectrum. However, the NIVA instrument seemed to overestimate b_b around 620 nm, and the DMI was completely off in the red 676 nm channel. This was also confirmed during two cruises in April and June 2002. Fortunately, this overestimation seems very stable and the correlation between GKSS and DMI instruments is excellent.

2. INTRODUCTION

As part of the MAVT work, the PlymCal-2 workshop was held at PML from 10-15 June 2002. A number of instruments were compared including Hydroscats, AC-9's and spectroradiometers. Also water samples were taken for comparison of water constituents concentration. The backscattering measurements are reported here. These were made at sea in both Case 1 and Case 2 waters, and in the lab with a controlled experiment in a tank.

Four institutions participated with Hydroscat instruments: the Danish Meteorological Institute (DMI), the GKSS Forschungszentrum, the Norwegian Institute for Water Research (NIVA) and the Plymouth Marine Laboratory (PML). The various Hydroscats vary in age; they are from 1997-2002 and number of channels, with either two, four or six wavelengths.

Table 1 below shows the configuration of the various Hydroscats, including year of purchase and wavelength channels.

Table 1: Hydroscat Configurations

Wavelength (nm)	**415**	**440** **442**	**488**	**510**	**550** **555**	**620**	**671** **675** **676**	**871**
Institution								
DMI HS2-1999			v				v (676)	
GKSS HS4-1997	v	v (440)		v			v (675)	
NIVA HS6-2001		v (442)	v	v	v	v	v (676)	
PML HS6-2002		v (442)	v		v	v	v (671)	v

In addition, a number of measurements were made during two REVAMP – cruises. The first one was conducted in April 2002 with M/S Heincke mainly in the German Bight and the central North Sea with the participation of GKSS and DMI, and one in June 2002 with M/S Belgica in Belgium coastal waters and the English Channel with the participation of PML and DMI.

3. METHOD

3.1 Principle of backscattering measurement

The principle of the Hydroscat is to estimate the total backscattering from a measurement of scattering at one single angle, 140° [1], as described in eq.1 (spectral notation omitted for simplicity):

$$b_b \;=\; 2p \;\cdot\; c(q) \;\cdot\; b(q) \tag{1}$$

where b_b is the total backscattering coefficient and ß (?) the volume scattering function (VSF). ?= 180°- θ_s, with θ_s being the solar zenith angle in water. The function $\chi(\theta)$ depends on the sensor geometry and varies only slightly and linearly around 120° [2], and the measurement at 140° can therefore be used with a great deal of confidence as it is not to far from the 120°. Both [1] and [2] find $\chi(140°) = 1.08$.

As the light is attenuated while travelling between the emitter and receiver of the instrument, a sigma-correction is used to compensate for this effect, which would otherwise lead to an underestimation of backscattering. The sigma-correction, as currently implemented in the Hydroscat controlling software, Hydrosoft2.5x is estimated by eq.2:

$$s \;=\; k_1 \cdot e^{\left(k_{\exp} \cdot K_{bb}\right)} \tag{2}$$

k_1 is a calibration parameter that compensates for the attenuation in the water used for the calibration. $k_{\exp}$ is a calibration parameter which is specific to the individual instruments, and K_{bb} is the attenuation coefficient of light travelling through the instrument's sensing volume, which depends on local water properties. Calculation of sigma requires that K_{bb} is measured or estimated using, eq.3:

$$K_{bb} \;=\; a + 0.4 \cdot \frac{b_b}{\tilde{b}_b} \tag{3}$$

In which, $\tilde{b}_b$ is the backscattering ratio (the ratio of backscattering to total scattering) is estimated from the raw backscattering measurement or specified by the user, default $\tilde{b}_b$ = 0.015, and *a* is the absorption coefficient modelled by, eq. 4:

$$a(l) \;=\; a_w(l) + \left\lfloor 0.06 \cdot a_{ph}{}^{*}(l) \cdot C^{\;0.65} \right\rfloor \cdot \left\lfloor 1 + 0.2\, e^{(-S_{ys} \cdot (l-440))} \right\rfloor + a_d(400) \cdot\; e^{\;(-S_d\;(l-400))} \tag{4}$$

In which a_w is the absorption of pure water, a_{ph}* the specific phytoplankton absorption coefficient, C the chlorophyll concentration, a_d the detritus absorption coefficient and *S* the exponential slope value for yellow substance (S_{ys}) and detritus (S_d), respectively.

Default values are: 0.014 and 0.011 for S_{ys} and S_d, respectively, C = 0.1 and a_d (400) = 0.01. These can be adjusted, as can the spectra for a_w and a_{ph}*.

3.2 Deployment during PlymCal-2

The first part of PlymCal-2 was carried out onboard R/V Squilla on a relatively cloudy and misty day. The Case 1 station was approximately 15 km outside Plymouth harbour and the Case 2 stations only a few km from the harbour close to the coast. Three of the Hydroscats were mounted vertically on the same horizontal crossbar about 30 cm apart, while the last (GKSS) instrument was lowered of a separate frame, 1-2 meters away from the crossbar. At the Case 1 station measurements were carried out for 22 minutes, while data for 7 minutes were collected at the Case 2 station. Data were processed to insure accurate cut-off of data collected while lowering and retrieving of the instruments. In addition, in order to filter out extreme spikes in the data, data outside +/- 3 standard deviations from the mean were excluded.

The second part of PlymCal-2 involved the measurements carried out in a tank in the laboratory. The tank was approx. 1 x 1 x 1 m. The instruments were deployed separately and data were recorded for 2 minutes, firstly with a TSM (total suspended matter) concentration of 1 mg/l in the tank, and secondly with a concentration of 5 mg/l TSM. A pump was used to circulate/mix the water and keep the material in homogenous suspension, but care was also taken to avoid creating too many bubbles.

3.3 Deployment during REVAMP cruises

During two REVAMP cruises in April and June 2002, on R/V Heincke and R/V Belgica, respectively, deployments were carried a few meters apart on separate frames. During the Heincke cruise, the DMI-HS2 instrument measured profiles at discrete depths of 1, 3 and 5 meter for approx. 30 seconds at each depth, while the GKSS-HS4 was installed on the CTD-frame making profiles from the surface to the bottom (often in the order of 20-30 meters). Figure 1 shows the stations visited during the Heincke cruise mainly in the German Bight and Central North Sea.

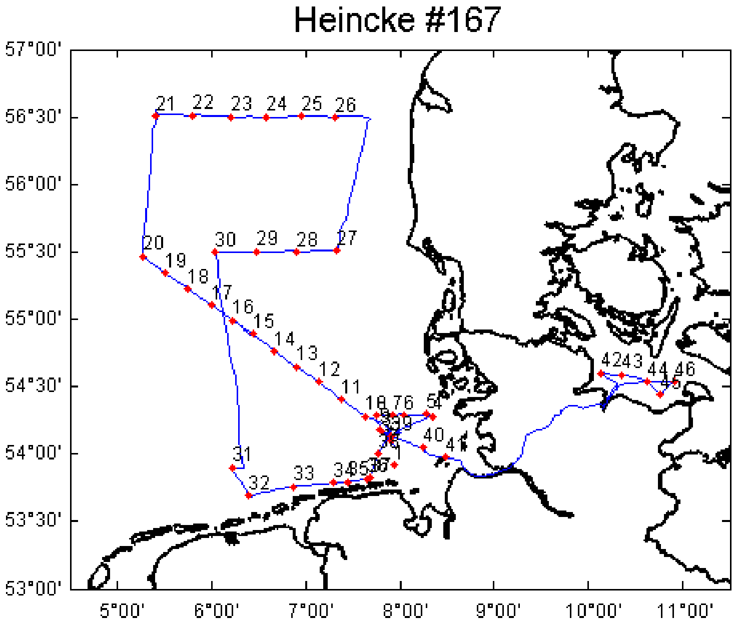

Figure 1: M/S Heincke cruise-plan April 2002 (Courtesy : Wolfgang Schoenfeld, GKSS)

In the section below, the average DMI values from 3-6 meters are compared to the average GKSS values from 1-10 meters at each station.

During the Belgica cruise, conducted by the MUMM- institute the PML-HS6 and DMI-HS2 instruments were lowered simultaneously to discrete depth where two minutes of data were recorded at 1, 3, 5, 7 and 9 meters depth.

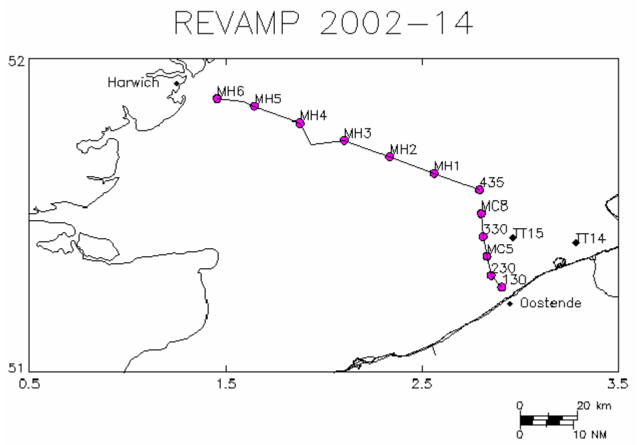

Figure 2: M/S Belgica cruise-plan June 2002 (Courtesy: Kevin Ruddick, MUMM)

Figure 3 shows an example of a b_b-data file before any processing. The instrument is switched on and off on the deck which causes the major spikes at the beginning and end of the cast in Figure 3. These are filtered out by selecting only data below 0.5 – 1.0 m.

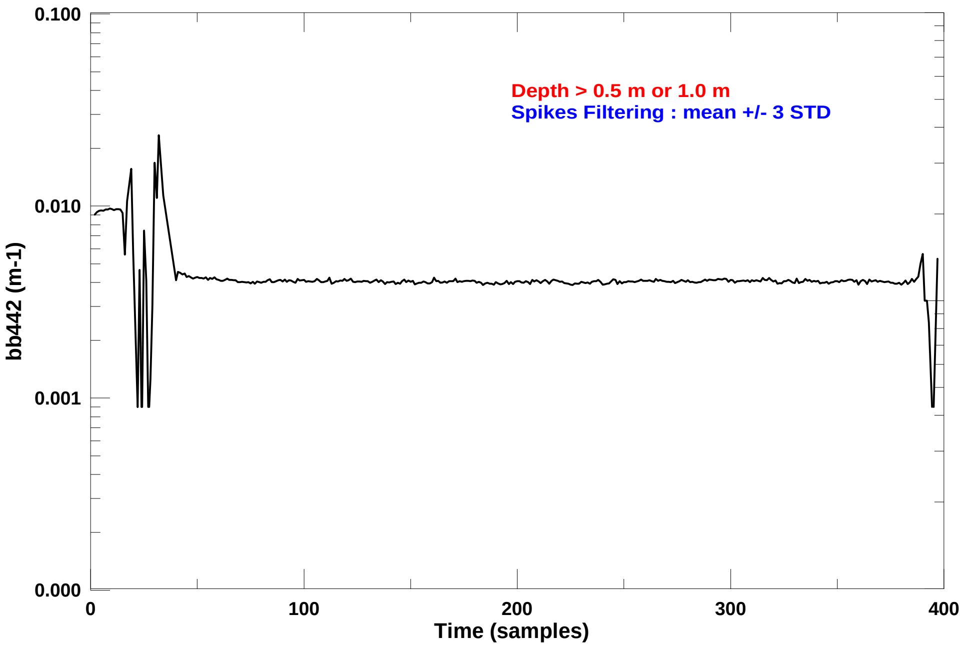

Figure 3 : Raw b_b-data file before cut-off in the beginning and end of the cast.

Hereafter, any remaining major spikes are removed by selecting data within +/- 3 standard deviations from the mean. Figure 4 shows the example of a HS-6 file from PlymCal-2 after this filtration. The motion of the ship can be seen as variations in depth from approximately 2.2 – 3.1 m during the entire 20 minute cast. Most of the time, the variations are smaller, from approximately 2.6 – 3.0 m. All six b_b (?) recordings are quite stable, with only minor variations, and b_b decreases slowly from 442 nm to 871 nm.

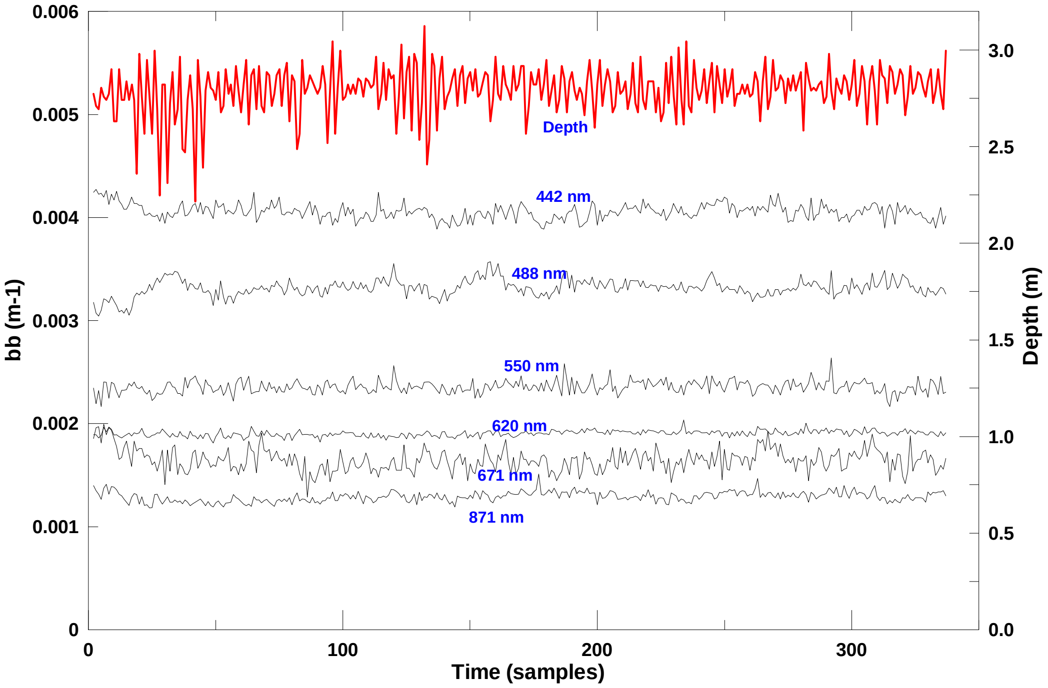

Figure 4: Example of b_b-data file from a HS-6 during PlymCal-2 after cut-off and spikes filtering.

4. RESULTS

4.1 Results from PlymCal-2 – Mean values of b_b.

Table 2 shows the mean depth and mean b_b - values at 488 and 676 nm recorded by the various instruments at the Case 1 station which were the wavelengths that all instruments measure, except for GKSS, which does not have a 488 nm channel, so the value at 488 nm has been interpolated from the 440 and 510 nm channels. Also, it should be noted that the exact position of the red channel varies, so that DMI and NIVA records at 676 nm, PML at 671 nm and GKSS at 675 nm. No corrections have been applied to account for the minor differences caused by this.

Table 2 : Case 1 station – Mean Depth and Bb – values (22 min. of measurements)

	DMI	**GKSS**	**NIVA**	**PML**
Depth [m]	3.3	3.0	3.4	2.8
b_b (488) [m^{-1}]	0.0036	0.0035	0.0038	0.0033
b_b (676) [m^{-1}]	(0.0030)	0.0017	0.0019	0.0016

Depth recordings range from 2.8 – 3.4 meters. The DMI values are known to be accurate, so the PML depth may be a bit low. GKSS instrument was on a separate frame so the 3.0 m value may be correct. Bb (488) values are in very good agreement ranging from 0.0033 – 0.0038. Bb (676) values of GKSS, NIVA and PML are in good agreement while the DMI value of 0.0030 is nearly a factor two higher (therefore the parenthesis). The 676 nm channel of the DMI instrument is generally suspicious; for instance it broke down shortly after the instrument was acquired. Table 3 shows the same as Table 2 for the Case 2 station.

Table 3 : Case 2 station – Mean Depth and Bb – values (7 min. of measurements)

	DMI	**GKSS**	**NIVA**	**PML**
Depth [m]	1.2	1.0	1.2	0.8
b_b (488) [m^{-1}]	0.0390	0.0295	0.0405	0.0338
b_b (676) [m^{-1}]	(0.0506)	0.0259	0.0284	0.0250

The results in Table 3 show that there was a difference of factor of 10-15 in backscattering between the two sites depending on wavelength. Depth values show the same picture as Table 2. B_b (488) shows somewhat larger differences than in Table 2, but again DMI and NIVA values are slightly higher than the NIVA and GKSS values. B_b (676) values have smaller variations, except again the DMI value of 0.0506.

4.2 Results from PlymCal-2 – Spectral variations of b_b.

Figure 5 shows the spectral variations of the data from both the Case 1 and Case 2 stations. In general the Hydroscat are in reasonably good agreement. PML and GKSS results show the same spectral shapes, while NIVA is similar except for the 620 nm channel. Also both NIVA and DMI values are slightly higher in all channels and again the red DMI channel at 676 nm seems to be far off compared to the others.

The results from the tank experiment in the laboratory are shown in Figure 6. Much of the same tendencies are seen for both the TSM concentrations of 1 and 5 mg/l, but the scatter between the instruments is larger. This was somewhat unexpected, since the controlled environment should have resulted in smaller deviations. The reason for this may be reflections from the sides and bottom of the relatively small tank. A future additional experiment with a larger tank would be preferable in order to confirm this. In addition, two of the six channels of the NIVA instrument saturated or failed, so data from four channels only were available from this instrument.

4.3 Results from REVAMP cruises

During the Heincke-cruise, simultaneous data-recordings with the DMI-HS2 and the GKSS-HS4 were made at 17 of the 40 stations. Scatterplots of b_b (488) and b_b (676) are shown in Figure 7 and 8. It should be noted again that the GKSS values were interpolated from values at 440 and 510 nm. However, there is excellent agreement between the two even over nearly 3 orders of magnitude in absolute range. Correlation coefficients are $r^2 = 0.972$ and $r^2 = 0.989$ for b_b (488) and b_b (676) respectively. The DMI values are consistently higher than the GKSS values which confirms the results from the PlymCal-2 intercalibration. The DMI blue channel is off by 23 % and the red is off by 85 %. Although, the large offset due to calibration is not very satisfactory, the fact that this is stable over the entire range, is actually quite satisfactory.

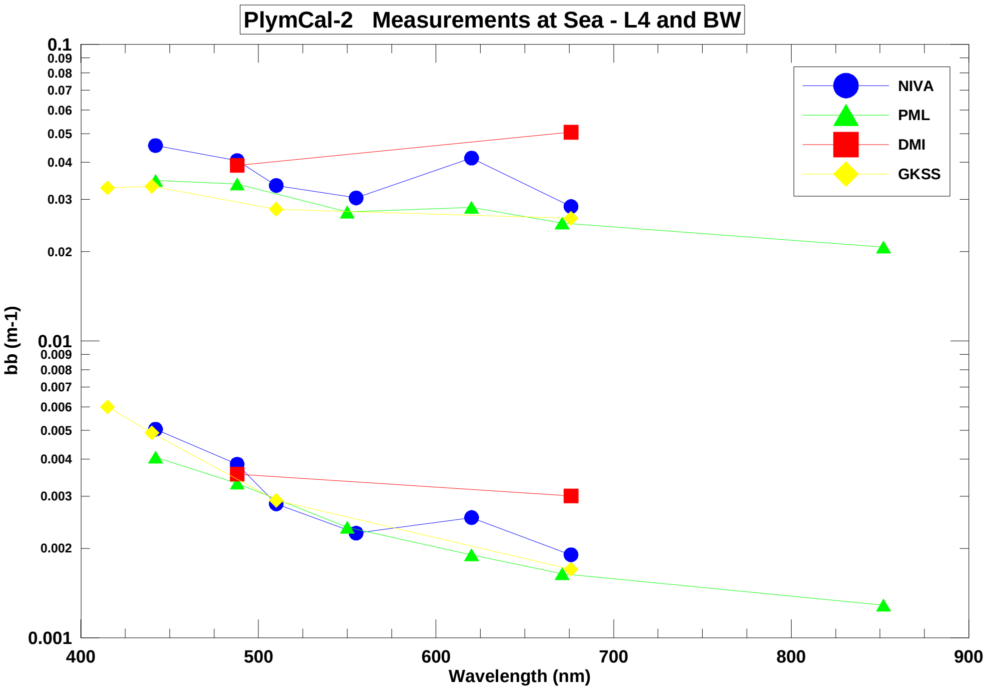

Figure 5: Spectral variations in measured bb at the Case 1 and Case 2 stations

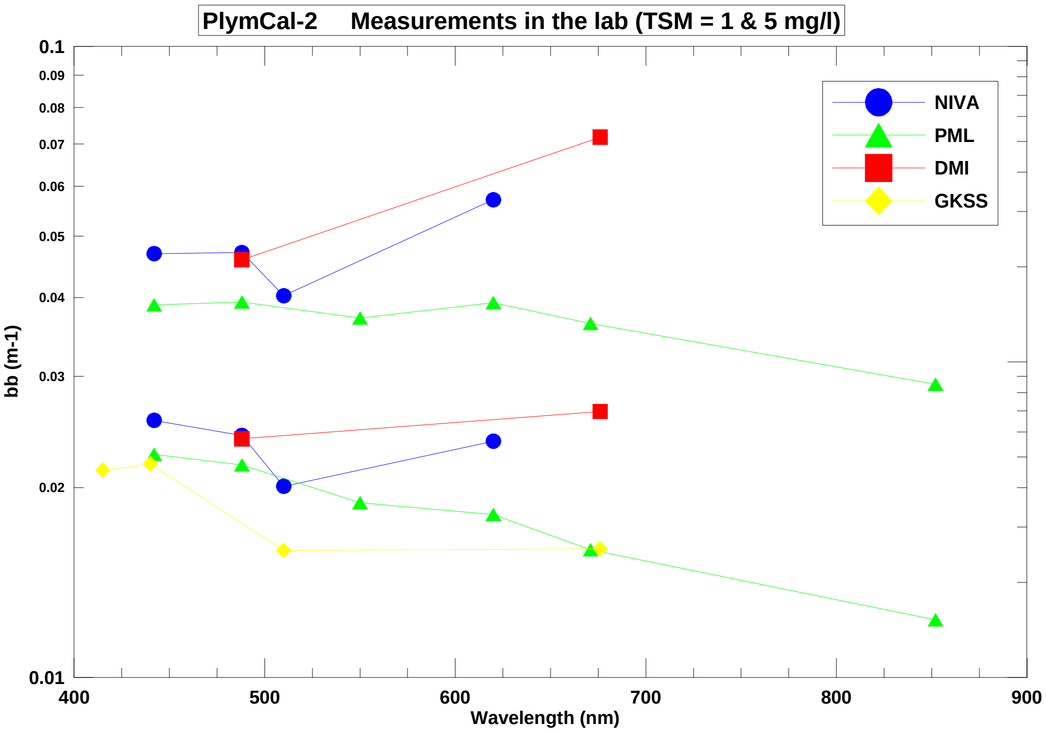

Figure 6: Spectral variations in measured bb during the laboratory experiment

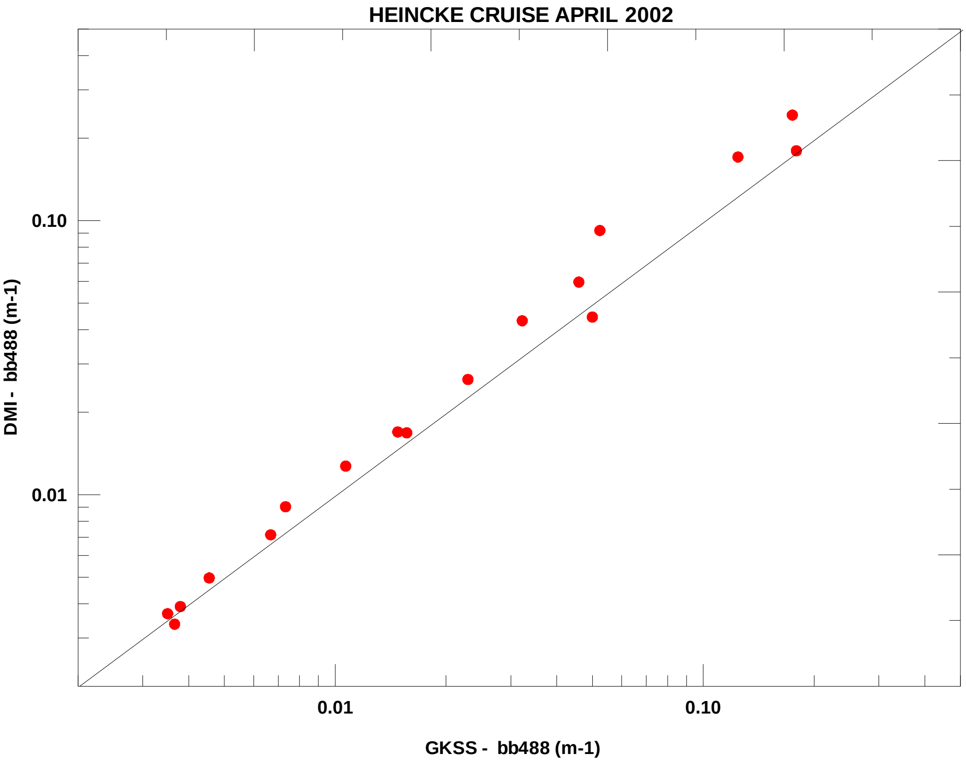

Figure 7: Scatterplot of GKSS and DMI values of b_b at 488 nm (m^{-1})

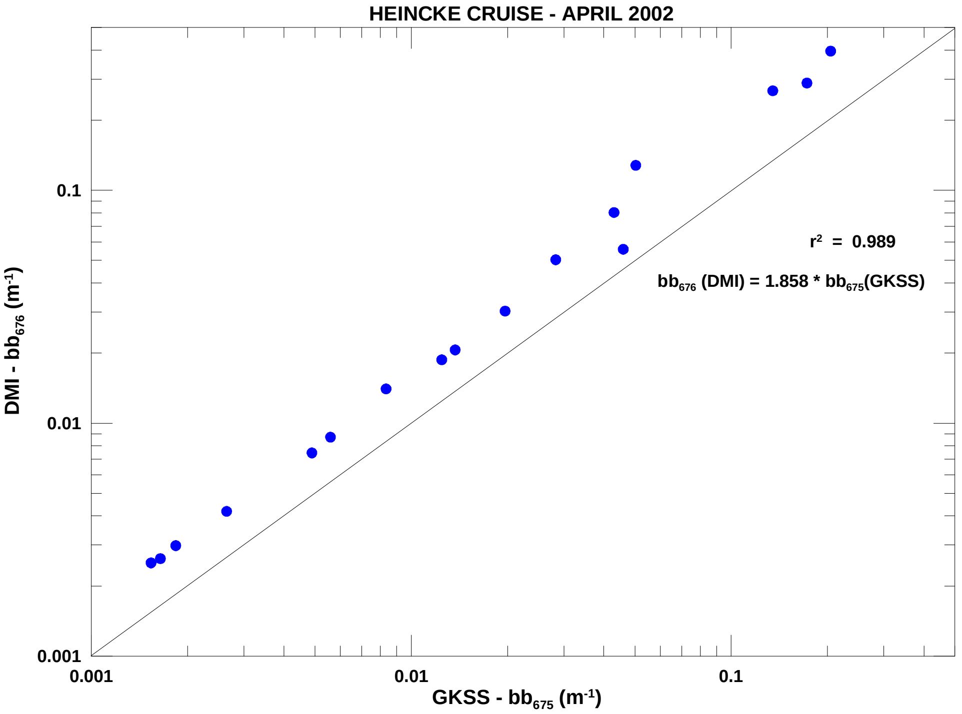

Figure 8: Scatterplot of GKSS and DMI values of b_b at 676 nm (m^{-1})

It should still be noted that the GKSS data were not sigma-corrected, and this accounts for 5.2 % of the observed differences. Exact values applied in the sigma-correction are given in Table 4.

Table 4: Applied Sigma Correction Parameters

	Hydroscat Default	DMI	GKSS	NIVA	PML
$a_d(400)$	0.01	1.0	-	0	0.01
$b_b^{\sim}(?)$	0.015	0.015	-	0.015	0.015
C (CHL-Conc.)	0.1	0.1	-	0	0.1
S_d	0.011	0.011	-	0	0.011
S_{ys}	0.014	0.014	-	0	0.014
G	4.32	4.32	-	4.0	4.32
?	1.08	1.08	-	1.08	1.08

During the M/S Belgica cruise in Belgian coastal waters and the English Channel simultaneous measurements with the PML-HS6 and the DMI-HS2 were made. Many stations were made with the PML-HS6, but unfortunately the cable on one of the DMI instruments was damaged on the first day of deployments, so data from only three stations were collected with both instruments. These measurements are shown in Figure 9.

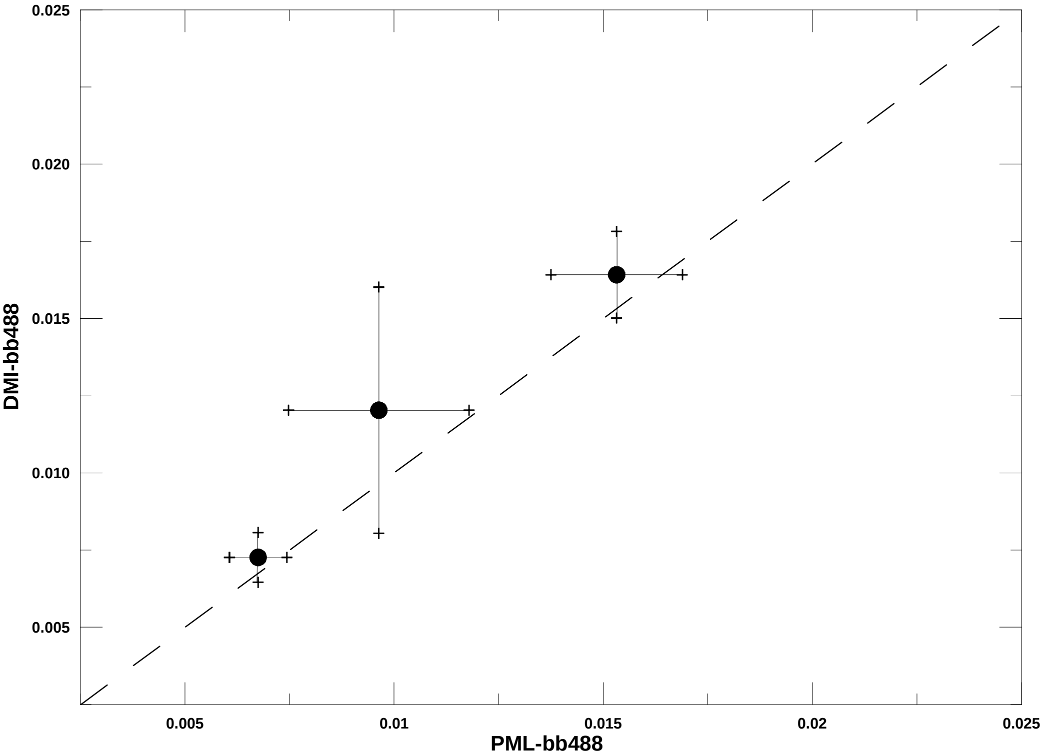

Figure 9: Scatterplot of PML and DMI values of b_b at 488 nm (m^{-1}) from M/S Belgica cruise including mean values and standard deviations

The overall results are the same as in the PlymCal-2 and the Heincke cruise analysis; the agreement between the two is good and DMI values are somewhat higher. The station where data from the two instruments deviate the most from each-other also has the highest standard deviations. The fact that the standard deviation is nearly equally large in both directions suggests that the water was very heterogeneous. The fact that the two instruments were lowered separately a few meters apart means that there were small differences in actual depth and therefore the actual watermasses recorded and that the variation in b_b *(488)* was due to fluctuating densities of particulate matter..

5. CONCLUSIONS

In general, the Hydroscat are in reasonably good agreement with each other both spectrally and in absolute values with a few exceptions. The GKSS and PML agree the best, while the DMI and NIVA instrument show slightly higher values. In addition the red DMI channel at 676 nm is far off compared to the others in requires calibration. The NIVA 620 nm channel also seem to overestimate.

Signal variations are higher during the laboratory experiment than during the measurements at sea, possibly due to noise originating the scattering by the walls and bottom of the tank.

Results from the REVAMP cruises (GKSS-M/S Heincke) and (MUMM-M/S Belgica) confirms the PlymCal-2 results tendencies (DMI higher than both GKSS and PML), but underlines also the excellent correlation between the instruments.

The application of varying sigma-correction accounted for up to 5 % of the differences observed. Even though this is a small correction, realistic sigma-correction values should be applied, particularly in turbid and/or highly absorbing waters (Case 2 waters), and also in any future b_b intercomparisons.

6. ACKNOWLEDGEMENT

The authors would hereby like to thank all the colleges participating in the PlymCal-2 for an interesting workshop and experiment and especially Gerald Moore for co-organising the event. In addition, we thank in particular Roland Doerffer and Kevin Ruddick for arranging the work on the GKSS and MUMM cruises within the REVAMP project. Finally, Jean Paul Huot (ESA) should be thanked for supporting the MAVT work and the EU-commission for funding the REVAMP project headed by Steef Peters. NIVA's activities in the intercomparison was also supported by ESA and Norwegian Space Centre (PRODEX contract no. 14849/00/NL/Sfe(IC).

7. REFERENCES

1. **Maffione, R. A. & Dana, D. R. (1997)**: Instruments and methods for measuring the backward-scattering coefficient of ocean waters. *Applied Optics, Vol.36 (24)*, 6057-6067.

2. **Oishi, T. (1990)**: Significant relationship between the backward scattering coefficient of sea water and the scatterance at 120°. *Applied Optics, Vol.29*, 4658-4665.