The Forel-Ule scale revisited spectrally: preparation protocol, transmission measurements and chromaticity

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The Forel-Ule colour comparator scale has been applied globally and intensively by oceanographers and limnologists since the 19th century, providing one of the oldest oceanographic data sets. Present and future Forel-Ule classifications of global oceanic, coastal and continental waters can facilitate the interpretation of these long-term ocean colour data series and provide a connection between the present and the past that will be valuable for climate-related studies.

Within the EC-funded project CITLOPS (Citizens' Observatory for Coast and Ocean Optical Monitoring), with its main goal to empower end-users, willing to employ community-based environmental monitoring, our aim is to digitalize the colours of the Forel-Ule scale to establish the colour of natural waters through smartphone imaging. The objective of this study was to reproduce the Forel-Ule scale following the original recipes, measure the transmission of the solutions and calculate the chromaticity coordinates of the scale as Wernand and Van der Woerd did in 2010, for the future development of a smartphone application. Some difficulties were encountered when producing the scale, so a protocol for its consistent reproduction was developed and is described in this study. Recalculated chromaticity coordinates are presented and compared to measurements conducted by former scientists. An error analysis of the spectral and colourimetric information shows negligible experimental errors.
[DOI: http://dx.doi.org/10.2971/jeos.2013.13057]

Keywords: Forel-Ule, colour of water, chromaticity, spectral transmission, optical properties

1 INTRODUCTION

Water colour measurements are based on multi- and hyper spectral measurements conducted in the field and from space. A simpler approach to determine the colour of natural waters is by means of the Forel-Ule (*FU*) colour comparator scale. This scale has been applied globally and intensively by oceanographers and limnologists since the 19th century, providing one of the oldest oceanographic data sets.

F. A. Forel first created 11 standards (*FU* 1-11) to classify blue to green waters [1] mixing different proportions of blue (copper sulphate) and yellow solutions (potassium chromate) ammonia and distilled water. W. Ule (1892, 1894) [2, 3] complemented the scale by adding 10 additional colours (*FU* 12-21), varying between blue-green to brown. Ule initially published the mixing proportions in 1892, where different percentages of brown solution prepared with cobalt sulphate were added to a basic green solution (35% blue, 65% yellow; *FU* 11). However, taking into account the oceanographers recommendations, Ule proposed a new prescription for the preparation of the scale standards in 1894 [2]. This modification was not mentioned by Forel in Le Léman published in 1895 [1], which could have led to faulty reproductions of the scale by those following the recipe published in that book. The directions for the correct mixing of the chemical compounds in these pub-

lications are scarce and a description of the exact colours that should be obtained is not facilitated. Hence, a more detailed protocol for the preparation of the scale will be very useful to reproduce the scale and obtain the same colours consistently. In 1930, Rosen published a description of the preparation of the scale [4] with additional details on the mixing of the chemicals compounds and transmission measurements of the 21 scale liquids, useful for the reproduction of the scale.

Within the EC-funded project CITLOPS (Citizens' Observatory for Coast and Ocean Optical Monitoring), with its main goal to empower end-users, willing to employ community-based environmental monitoring, our aim is to digitalize the colours of the Forel-Ule scale to establish the colour of natural waters through smartphone imaging. To accomplish the implementation of a specific "ocean colour" smartphone application (App) that could be distributed among citizens, the aim of this study was to first reproduce the original scale developed by Forel [1] and Ule [2] following their published recipes and describe a detailed protocol of the procedure to facilitate the reproduction of the scale in the future. The second objective was to measure the transmission of the scale liquids and calculate the chromaticity coordinates of the new scale to digitalize the colours of the *FU* solutions. For this pur-

pose, Rosen's recommendations for the reproduction of the scale were followed and the transmission measurements of the coloured liquids obtained in this study were compared to his findings and to the results published by Wernand and Van der Woerd [5].

2 MATERIALS AND METHODS

2.1 Preparation of the *FU* scale

The original recipes for reproducing the liquids are published in Forel's monograph [1] and Ule's article [2]. Three basic solutions were initially prepared using MilliQ water, ammonia (28-30% NH_3 in H_2O) and in the form of crystals, copper sulphate ($CuSO_4 \cdot 5H_2O$), potassium chromate (K_2CrO_4) and cobalt sulphate ($CoSO_4 \cdot 7H_2O$). These three basic solutions are then mixed in different proportions to obtain the 21 coloured solutions of the scale. The concentrations of the three standards used for the preparation are shown in Table 1 and the mixing ratios of the 21 *FU* scale solutions are shown in Table 2 and Table 3. The crystals are added to the ammonia solution and this solution is brought to the desired volume (1 or 2 litres) by adding MilliQ water.

The blue and yellow solutions are prepared by adding the chemical compounds (copper-sulphate and potassium-chromate respectively), followed by the water and the ammonia solution while stirring. A white precipitate could be observed in the blue solution when the water is added; to make it disappear some extra drops of ammonia should be added.

The preparation of the brown solution is more delicate. The compounds need to be mixed in a particular order and in the appropriate proportions to obtain the desired brown colour. First, the cobalt-sulphate powder has to be added to the mixing container, and then 50 ml of water (if preparing 2 litres) should be added, while stirring, to obtain a red-pinkish solution (Figure 1(a)). The 50 ml of ammonia should be added when all the powder is dissolved, resulting in a dark brown solution (Figure 1(b)). This solution should be allowed to sit for 1 hour, after that time, the remaining water should be added slowly while stirring (approx. 900 ml). It is important that all powder dissolves and results in a clear brown solu-

tion. In case a green precipitate is obtained, it means that a part of the cobalt did not mix with the water and the final solution will not have the desired brown colour (Figure 2 and the visual result after filtering is shown in Figure 3). If it happens that a green precipitate is formed when the compounds are mixed, the solution should be prepared again because this effect is not reversible.

The solutions are then mixed in glass bottles according the proportions shown in Tables 2 and 3. After mixing, minute brown particle could still be observed in mixtures *FU*12 to *FU*21. To guarantee particle free solutions to be sealed for the new *FU* scale and conduct accurate transmission measurements, *FU*12 to *FU*18 were filtered over 0.2 μm filters. The result of this exercise is shown in Figure 4.

The final solutions are filled into glass tubes with a diameter of 10 mm, sealed (in our case with 'Ruplo Lijmtechniek' adhesive) and fixed in a holder (Figure 5) with a white background
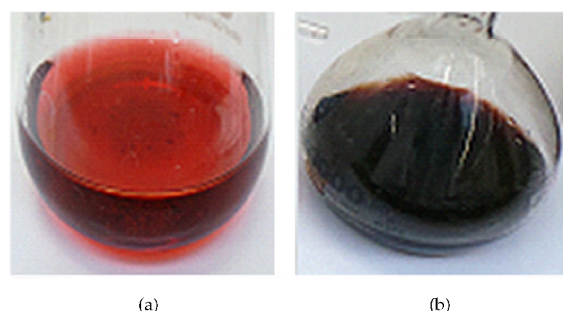

FIG. 1 Cobalt-sulphate (5 g) mixing with 50 ml of H_2O (a) and extra 50 ml of ammonia (b).
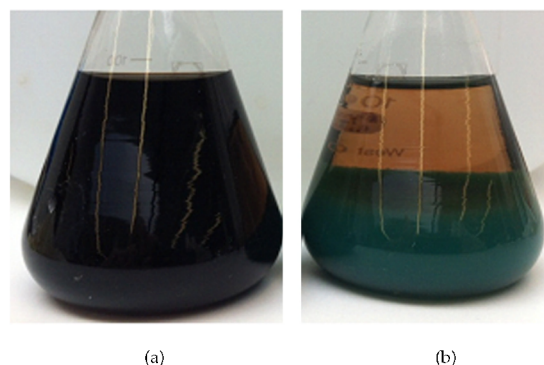

FIG. 2 a) The basic brown solution when mixed with 2.5% of H_2O + 2.5% of ammonia in the correct order (dark brown solution) and a wait of 1 hour before adding the rest of the H_2O, and (b) a brown solution for which all chemical components were mixed at the same time, resulting in a solution with a green precipitate.
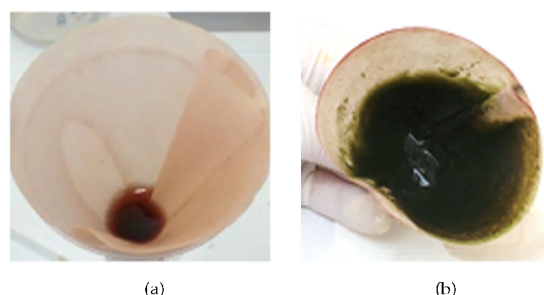

FIG. 3 Minimal filter residue in case the brown solution is chemically mixed correctly (a). A considerable green residue is formed when all the components (cobalt-sulphate, ammonia and MilliQ H_2O) are mixed instantly (b).

Blue solution	For 2 litres
copper sulphate ($CuSO_4 \cdot 5H_2O$)	10 g
ammonia (28–30% NH_3 in H_2O)	50 ml
MilliQ H_2O	Add up to 2 l
Yellow solution	**For 2 litres**
potassium chromate (K_2CrO_4)	10 g
MilliQ H_2O	Add up to 2 l
Brown solution	**For 2 litres**
cobalt sulphate heptahydrate ($CoSO_4 \cdot H_2O$)	5 g
ammonia (28–30% NH_3 in H_2O)	50 ml
MilliQ H_2O	Add up to 1 l

TABLE 1 Chemical base solutions of the Forel-Ule scale for 1 and 2 liters.

Solution (%)	1	2	3	4	5	6	7	8	9	10	11
% Blue	100	98	95	91	86	80	73	65	56	46	35
% Yellow	0	2	5	9	14	20	27	35	44	54	65

TABLE 2 The mixing proportions (%) of copper-sulphate and potassium-chromate solutions to derive the *FU*-scale colours blue (*FU*1) to green (*FU*11).

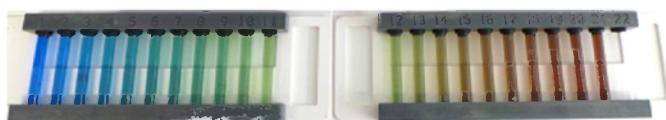| Solution (%)	12	13	14	15	16	17	18	19	20	21
% Blue	35	35	35	35	35	35	35	35	35	35
% Yellow	60	55	50	45	40	35	30	25	20	15
% Brown	5	10	15	20	25	30	35	40	45	50

TABLE 3 The mixing proportions (%) of copper-sulphate, potassium-chromate and cobalt-sulphate solutions to derive the *FU*-scale colours green (*FU*12) to brown (*FU*21).

FIG. 4 Two examples (*FU*12 and *FU*18) show minimal residue after a last filtration of the solutions over 2 μm pore size filters.

FIG. 6 Transmission measurement set-up: TriOS VIS-Spec Analyzer and quartz cuvette.

FIG. 5 Forel-Ule scale solutions filled into glass tubes and mounted on a white Perspex holder.

(white Perspex or white painted wood), a broad observation window at half way to look through and handles at each side. It is recommended to keep the scale in a the dark when not used, to avoid discoloration of the solutions, and preferably refrigerated around 5°C. A discoloration of previously prepared solutions [5] was observed 5 years after its production (kept in the refrigerator), so this period is considered to be the expected lifespan of the scale.

2.2 Spectral transmission measurements and colourimetry

The transmission of the basic and *FU* solutions were conducted as in Wernand and Van der Woerd's work [5] but using a TriOS VIS-Spec Analyzer with a resolution of 3.3 nm and using a quartz cuvette (12.5 × 12.5 × 45 mm; Figure 6) to pour the liquids in, as shown in Figure 6. The actual path length of the cuvette is considered to be 10 mm. The device is composed of a halogen lamp of 20 watts. In Figure 5, I_0 is the flux leaving the light source and I the flux leaving the cuvette.

The procedure for the measurement and calculation of the transmission of the *FU* solutions as well as the calculation of the chromaticity coordinates were conducted in the same way as in [5]. More information on colourimetry and the calculation of tristimulus values and chromaticity coordinates can be found in Mobley's, Apel's, and Wyszecki and Stiles' publications [6]–[8].
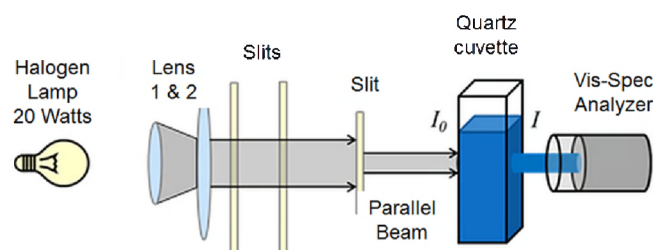
2.3 Error analysis

The error of the experimental set-up was assessed calculating the wavelength dependent bias between the two transmission measurements conducted for each scale and estimating the noise effect between measurement configurations. The potential impact of instrument noise on the actual colour was analysed by creating 50 synthetic spectra by adding random noise to the *FU* transmission curve and calculating the mean deviations in the chromaticity coordinates.

In addition, differences in *FU* colours were assessed considering the effect of the Quartz cuvette used for the measurements and the MilliQ H_2O on the *FU* colours. The difference in *FU* angles were calculated based on (1) the integral measurement of the cuvette with the *FU* solution, (2) the correction for the MilliQ H_2O and (3) the correction for the cuvette of different path lengths (8, 10, 12 mm). The incoming intensity (I_0) is attenuated by the absorption of the pure pigments (*FU*) and absorption and scattering by the MilliQ water (H_2O) and the cuvette itself (CUV) and:

$$I = I_0 T_{FU} T_{H_2O} T_{CUV} \quad (1)$$

Where I is the measured intensity I and T are the transmission functions that are a strong function of wavelength for *FU* and H_2O. The first option considers the integral transmission ($T_{FU} T_{H_2O} T_{CUV}$) to mimic closely the actual colour as seen by an observer. A reference measurement (Cuvette with MilliQ H_2O) was made to determine the product of ($T_{H_2O} T_{CUV}$) and subtracted to yield T_{FU}. To determine the impact of the absorption and scattering by pure water, the

transmission of MilliQ H_2O in the cuvette was calculated and added ($T_{FU}T_{H_2O}$) by:

$$T_{H_2O} = e^{(-TH(a+b))} \qquad (2)$$

Where TH is the path length of the cuvette, a is the absorption and b is the scattering (m^{-1}) extracted from [9]. Then, the arctangent of the chromaticity coordinates (in degrees) was calculated for three different path lengths 8, 10, and 12 mm, to account for a $\pm 20\%$ difference in the thickness of the cuvette.

3 RESULTS

Spectral transmission measurements of the freshly prepared FU scale mixtures were performed as described in the previous section. As we can observe in Figure 6, with the increasing amount of the basic yellow added to the blue basic solution, we can observe a shift towards higher wavelengths in the maximum of the $T_{FUN}(\lambda)$ (normalized transmission between 380 and 780 nm) and a magnitude increase of the depression observed around 600 nm for $FU1$ to $FU11$. With the addition of the brown basic solution we observe a rapid decrease of magnitude of the spectra. $FU11$ is shown in both top graphs of Figure 7(a) and 7(b), as the link between Forel and Ule's scales. This is also the basic green solution shown at the bottom of Figure 7(c) and $FU1$ is the basic blue solution.

Table 4 shows the CIE XYZ tristimulus values of the FU prepared for this study (FU NWV 2013) and used to estimate the chromaticity coordinates shown in Figure 8 (FU in MilliQ solution plus cuvette). The CIE XYZ tristimulus values are calculated using an equal-energy type of illuminant named "Type E", with equal CIE XYZ tristimulus values ($X = Y = Z = 1$) and equal chromaticity coordinates ($x = y = z = 1/3$). The type of illuminant can affect the colour appearance and for that reason it is important to use the same type of illuminant when comparing colours. More information on the standard types of illuminants and colorimetric calculations can be found in the ASTM (American Society for Testing and Materials) document E308-12 [10].

Figure 8 shows in addition to the chromaticity coordinates of the FU NWV 2013 scale, the coordinates calculated from the transmission spectra extracted from Rosen's article published in 1930 [4], and the coordinates calculated by Wernand and Van der Woerd [5]. The chromaticity diagram shows that the FU scale coordinates extracted from Rosen's and Wernand-Woerd's spectral measurements are similar to the FU coordinates of our scale, but with less saturation in general. Lines drawn from the white point through the FU loci intersect the boundary line, indicating the 'dominant wavelength' value for each standard (Table 5). We can see that $FU1$ and $FU11$ approximately match for the three scales, but show a different saturation. In the case of $FU12$ to $FU21$ we can see more differences, the first solutions match in colours but the differences increase towards the $FU21$ locus. Our scale has browner colours than the other two, but the spacing between the loci is more consistent compared to the other two scales, where some

overlapping of the loci can be observed (more concretely between $FU12$ and $FU15$).

Wernand et al. [11] determined the FU number from spectral measurements by calculating the angles of the FU chromaticity coordinates in a Cartesian coordinate system of the 21 FU numbers, using the arctangent between two vectors as expressed in equations 3 and 4. Thus, the angle (in radians) between the vector to a point with certain FU coordinates (x, y) the positive x-axis is calculated, giving higher angles in an anti-clockwise direction (Figure 6.3) and negative angles in a
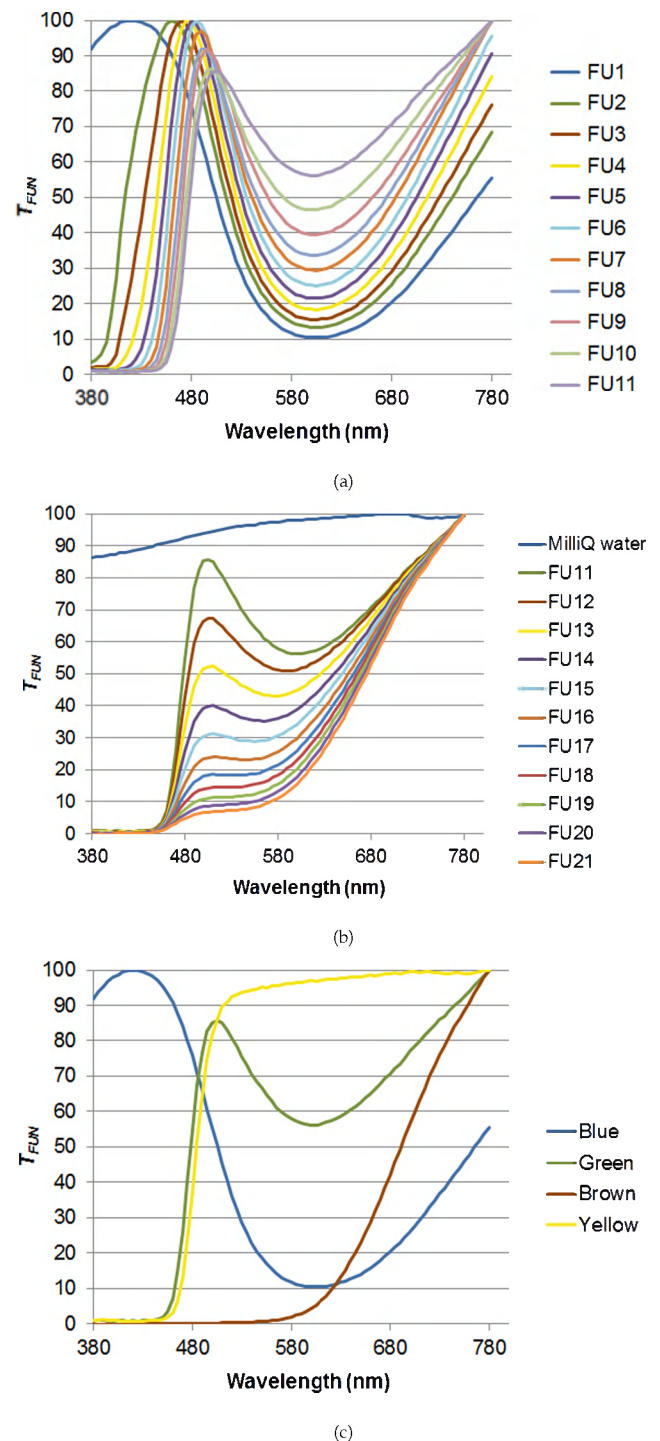

(a)

(b)

(c)

FIG. 7 Normalized transmission (T_{FUN}) between 380 and 780 nm of the 21 FU-tubes (NWV 2013; a and b) and the basic solutions (c), the blue solution corresponds to $FU1$ and green solution corresponds to $FU11$. This measurement includes the quartz cuvette and the FU solution.

	FU NWV 2013			FU Wernand-Woerd 2010			FU Rosen 1930		
	x	y	Dominant wavelength (nm)	x	y	Dominant wavelength (nm)	x	y	Dominant wavelength (nm)
FU1	0.191	0.167	468.0	0.189	0.161	468.0	0.208	0.185	468.0
FU2	0.199	0.200	475.0	0.196	0.194	475.0	0.215	0.218	476.0
FU3	0.210	0.240	481.0	0.213	0.255	482.0	0.227	0.251	481.0
FU4	0.227	0.288	485.5	0.229	0.301	487.0	0.243	0.297	486.0
FU5	0.246	0.335	491.0	0.242	0.331	491.0	0.263	0.340	492.0
FU6	0.266	0.376	498.5	0.263	0.373	498.5	0.286	0.378	504.0
FU7	0.291	0.412	515.0	0.290	0.415	520.0	0.307	0.410	526.0
FU8	0.315	0.440	540.0	0.311	0.439	540.0	0.326	0.439	550.0
FU9	0.337	0.462	553.0	0.337	0.463	555.0	0.346	0.456	556.0
FU10	0.363	0.476	561.0	0.363	0.480	562.0	0.369	0.472	562.5
FU11	0.386	0.487	565.0	0.388	0.490	567.0	0.389	0.485	565.0
FU12	0.402	0.481	569.0	0.394	0.488	568.0	0.389	0.477	566.0
FU13	0.416	0.474	570.5	0.397	0.486	568.5	0.396	0.466	569.0
FU14	0.431	0.466	572.0	0.404	0.482	569.5	0.398	0.460	570.5
FU15	0.446	0.458	575.0	0.410	0.478	570.5	0.406	0.450	572.0
FU16	0.461	0.449	578.0	0.418	0.472	572.5	0.410	0.442	573.0
FU17	0.475	0.441	580.5	0.427	0.466	574.5	0.414	0.431	575.0
FU18	0.489	0.433	582.0	0.440	0.458	576.0	0.418	0.419	578.0
FU19	0.503	0.425	585.0	0.453	0.448	579.0	0.422	0.410	580.0
FU20	0.516	0.416	587.0	0.462	0.440	580.0	0.418	0.393	582.5
FU21	0.528	0.408	589.0	0.473	0.429	582.0	0.417	0.381	585.0
Blue	0.191	0.167	468.0	0.189	0.161	468.0	0.208	0.185	468.0
Yellow	0.434	0.493	572.5	0.436	0.496	572.5	- -	- -	- -
Green	0.386	0.487	565.0	0.388	0.490	567.0	0.389	0.485	565.0
Brown	0.646	0.350	605.0	0.498	0.383	592.0	- -	- -	- -

TABLE 5 Chromaticity coordinates, based on transmission measurements of the 3 FU scales prepared in this study, by [4] and [5]. The NWV 2013 FU chromaticity coordinates consider the transmission of the FU solution in MilliQ H$_2$O and the 10 mm Quartz cuvette.

clockwise direction. The radials are then multiplied by $180/\pi$ to get angles (α_i) in degrees.

$$i \in [1,21] \qquad (3)$$

$$\alpha_M = \arctan(y_i - y_W, x_i - x_W) \quad \text{modulus } 2\pi \qquad (4)$$

where α_M is the angle to be calculated, and "$y_i - y_W$" and "$x_i - x_W$" are the chromaticity coordinates of the spectral measurement with respect to the white point.

The angles between the white point and the FU chromaticity coordinates (Figure 8) were calculated using equation 5 as explained in Wernand et al.'s study [11]. Table 6 shows the angles calculated for the new FU chromaticity coordinates (NWV 2013) expressed as α_i^0 and the colour transition angles α_{iT}^0, calculated with the following equation:

$$\alpha_{iT} = \frac{\alpha_i + \alpha_{i+1}}{2} \qquad (5)$$

The α_{iT} can be then used to determine the FU number of a spectral measurement. For this, first the specral values measured need to be normalized and converted to chromaticity coordinates. Then, the angle α_M is calculated using Eq. 4 and compared to the twenty-one values of iT given in Table 6. A

loop for $i = 1$ to $i = 21$ can be applied and if the logical function 'If $\alpha_M > \alpha_{iT}$' is true for the first time reaching the angle α_{iT}, then the corresponding FU number can be attributed.

The experimental error analysis revealed a typical noise bias of 10^{-4} above 440 nm and a sudden increase to 4×10^{-4} below 440 nm, probably due a higher intrinsic instrumental error bellow that wavelength. In total, the experimental error considering the noise in between channels and the bias between the 2 transmission measurements, did not affect more than 0.022 degrees (when converted to the Cartesian system).

The correction of the FU measurements (with respect to the Quartz cuvette and the MilliQ H$_2$O) revealed an average difference of 1.78 degrees between the integral measurement of the FU solution ($T_{FU}T_{H_2O}T_{CUV}$) and when corrected for the cuvette, the MilliQ water and the path length. Figure 9 shows that a greater offset in degrees is observed when considering different path lengths (8, 10, 12 mm) mostly for FU 5 to 9 and FU 14 to 21 ($T_{FU}T_{H_2O}T_{CUV}$). Also, higher offsets are observed for the integral measurements ($T_{FU}T_{H_2O}T_{CUV}$) of FU 5 to 9 compared to the rest of the FU numbers, when the scattering and absorbance of the MilliQ H$_2$O is removed (T_{FU}). However, this offset is smaller than the spacing between FU-numbers' boundaries.

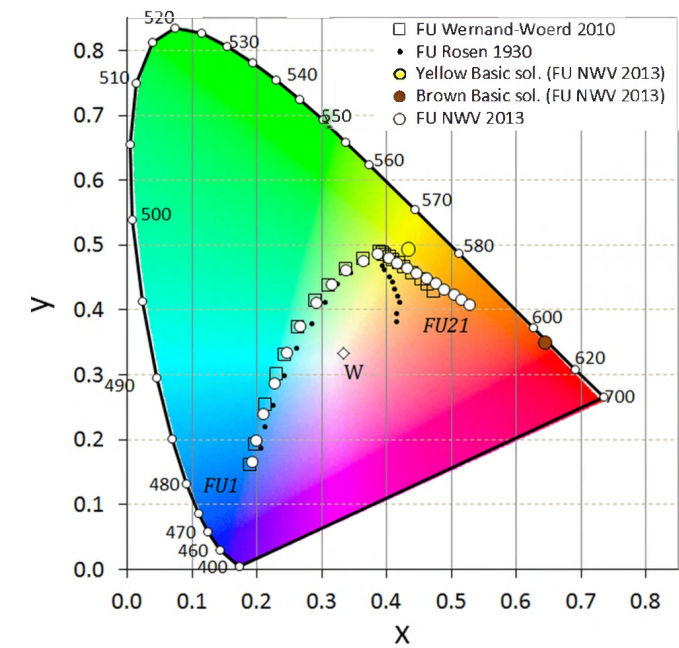FIG. 8 The CIE1931 chromaticity coordinates, based upon transmission measurements of the *FU* scale colours 1 to 21, including the white point (W, $x=y=1/3$) for the scale presented in this study (*FU* NWV 2013; white circles), the scale prepared by Wernand and Van der Woerd in 2010 (*FU* Wernand-Woerd 2010; squares) and the one prepared by Rosen in 1930 (*FU* Rosen 1930; black circles).

FIG. 9 *FU* angle degrees (a) and offset (b) calculated for the integral *FU* solution (T_{FU} T_{H_2O} T_{CUV}), the correction for MilliQ H_2O and cuvette (1_{FU}) and the correction for the $\pm20\%$ path length (8, 10, 12 mm T_{FU} T_{H_2O}).

4 DISCUSSION AND CONCLUSIONS

The Forel-Ule scale is used since the 19th century as a colour comparator to classify the colour of oceanic, coastal and continental waters. A large amount of data has been gathered all over the world covering the 1890–2000 period and stored in the U.S. National Oceanographic Data Centers World Ocean Database [12]. However, with the fast development of the low-cost radiometers during the last years, the ocean colour measurements have been shifting away from the *FU* scale, making it difficult to connect past and present ocean colour observations.

The aim of this study was to reproduce the scale as similarly as possible to the original one developed by Forel and Ule, improving the work conducted by Wernand and Van der Woerd and to measure the transmission of the *FU* solutions to calculate their chromaticity. Some difficulties were found during the preparation of the coloured solutions and since the creators of the scale provided limited indications on the mixing procedure of the chemical compounds and on the resulting colours that should be obtained, several tests were conducted. Rosen's publication in 1930 [4] provided more details on the steps to be followed than Forel and Ule, and also on the problems that we could encounter, such as the precipitation of the salts. His recommendations helped us establish the protocol described in this document and the transmission measurements of the *FU* solutions he published allowed us to compare

Tristimulus values *FU* NWV 2013			
	X	**Y**	**Z**
*FU*1	0.23721	0.20691	0.79546
*FU*2	0.21040	0.21137	0.63576
*FU*3	0.19016	0.21722	0.49808
*FU*4	0.17832	0.22699	0.38190
*FU*5	0.17715	0.24157	0.30178
*FU*6	0.18353	0.25932	0.24652
*FU*7	0.20457	0.28951	0.20942
*FU*8	0.23290	0.32496	0.18064
*FU*9	0.27374	0.37540	0.16397
*FU*10	0.33820	0.44347	0.14930
*FU*11	0.39397	0.49637	0.12981
*FU*12	0.35345	0.42256	0.10231
*FU*13	0.30720	0.34959	0.08124
*FU*14	0.25746	0.27786	0.06157
*FU*15	0.22907	0.23520	0.04971
*FU*16	0.19695	0.19217	0.03847
*FU*17	0.17039	0.15808	0.03000
*FU*18	0.15126	0.13398	0.02429
*FU*19	0.13130	0.11077	0.01880
*FU*20	0.11808	0.09532	0.01566
*FU*21	0.10452	0.08079	0.01255
Blue	0.23721	0.20691	0.79546
Yellow	0.87310	0.98158	0.13922
Green	0.39397	0.49637	0.12981
Brown	0.02840	0.01428	0.00009

TABLE 4 CIE Tristimulus (illuminant type E) values of the *FU* scale solutions developed for this study (*FU* NWV 2013) and used to calculate the chromaticity coordinates shown in Table 5.
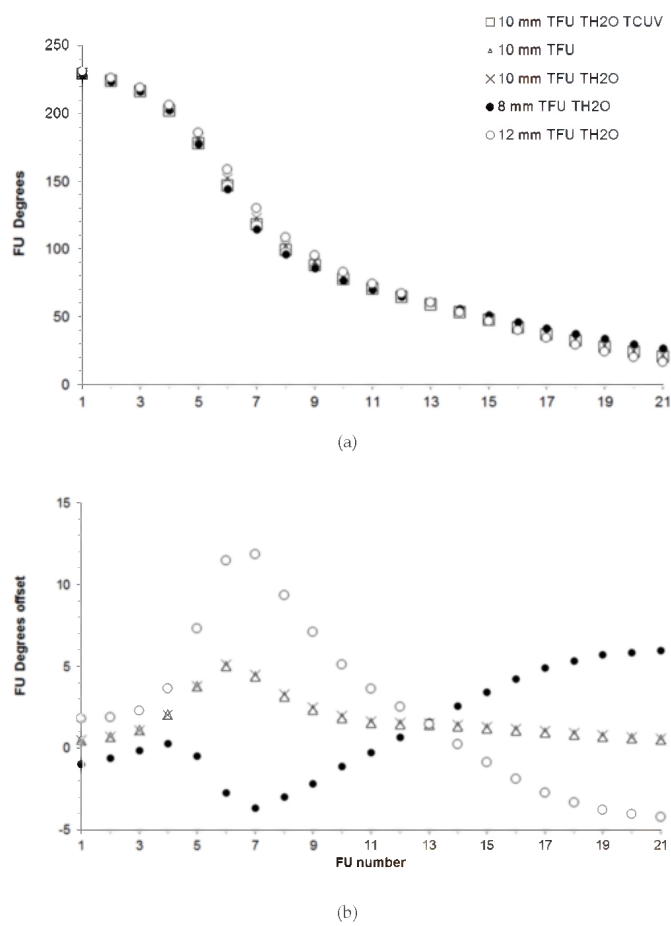
i	α_{iT}^0	For $i = 1$ to 21 If $\alpha_M > \alpha_{iT}$, then $FU =$
1	227.168	1
2	220.977	2
3	209.994	3
4	190.779	4
5	163.084	5
6	132.999	6
7	109.054	7
8	94.037	8
9	83.346	9
10	74.572	10
11	67.957	11
12	62.186	12
13	56.435	13
14	50.665	14
15	45.129	15
16	39.769	16
17	34.906	17
18	30.439	18
19	26.337	19
20	22.741	20
21		21

TABLE 6 Determination of the *FU*-number from known (x, y) chromaticity coordinates is achieved using given angle i; a loop for $i = 1$ to $i = 21$ is applied and if the logical function 'If $\alpha_M > \alpha_{iT}$' is true for the first time reaching the angle α_{iT}, then the corresponding *FU* number can be attributed.

it to the scale prepared by Wernand and Van der Woerd [5] and the one prepared for this study (NWV 2013). We initially found problems with the preparation of the brown solution, as a green precipitate was obtained when mixing the three components: cobalt sulphate, ammonia and MilliQ water. After several trials, we realized that the order and the initial mixing amounts were very important to obtain the brown solution. The ammonia had to mix well with the cobalt sulphate before the total water volume was added, otherwise a greenish precipitate was formed (Figure 3). The amount of precipitate formed could not be accounted for and a different shade of brown was obtained for every conducted trial. We assumed that the creators of the scale intended to have all of the cobalt sulphate (5 g for 1 litre) dissolved in ammonia solution to obtained the right brown colour, otherwise they would have indicated to add a lower amount of cobalt sulphate. In addition, Ule did not mention the exact amount of ammonia that should be included in the mixture nor the concentration of ammonia in solution, he just indicated to use "strong ammonia water". The *FU* solutions were filtered with a 0.2 μm filter to measure the transmission accurately, because the presence of particles suspended in the solution could have produced inaccurate transmission measurements. However, if the purpose of the production of the scale is to conduct field comparisons, as in the 19th century by the creators of the scale, it would not be necessary to filter the solution because these particles do not affect the colour of the solutions.

The brown mixing process was repeated several times until the same brown colour was obtained each time. However, as it can be observed in the chromaticity diagram, we ob-

tained a browner solutions than the obtained by Wernand-Woerd and Rosen (Figure 7). In the case of Wernand-Woerds scale the differences can be explained by the fact that they used the first recipe Ule published [3]. In the case of Rosen, the differences can be attributed to the measurement technique and the precision of the equipment used (transmission meter, cuvette, lamp, etc), as they were completed almost 75 years ago. Besides, as we can observe on the diagram, the spacing between the loci is less uniform for Wernand-Woerds and Rosens scales, compared to the new scale, which shows more uniform spacing (*FU*12-15). Hence, we considered the new scale to be more suitable for the digitalization of the *FU* colours and also to distinguish between the *FU* colour solutions when performing field measurements, since the overlapping of the chromaticity coordinates could complicate the comparisons.

The error analysis indicates a negligible experimental error, but shows a difference in colour related to the thickness of the container and the MilliQ water. This reveals the importance of using a similar tube type and size as the ones described by the creators of the scale, because they can affect the *FU* colours perceived by the observer.

The CIE XYZ values presented in Table 4 can be used to represent the colours of the scale in different colour spaces (or colour models), such as the standard RGB colour space (referred as sRGB), commonly used by the imaging industry. More information on the CIE system and the sRGB colour space can be found in Shanda's [13] and Süsstrunk's [14] publications, respectively.

Finally, it was decided to use the protocol described in this study for the preparation of the solutions and to consider the measurements performed as correct, because they followed the original recipes, we were able to reproduce the mixtures and they showed enough spacing between the loci to be able to distinguish the different *FU* scale numbers (more suitable for the digitalization of the scale). The *FU* scale reproduced will be used in the future to collect observations of natural waters and will function as a standard for a smartphone application that will be distributed among citizens.

5 ACKNOWLEDGEMENTS

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