Algorithm Theoretical Basis Document

ATBD 2.6

CASE 2 (S) BRIGHT PIXEL

ATMOSPHERIC CORRECTION

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Case II.S Bright Pixel Atmospheric Correction

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In waters dominated by sediment there is significant water leaving radiance in both the visible and near infrared (NIR). Atmospheric correction (AC) based on the concept of zero NIR water leaving radiance (dark pixel model) will fail because the extrapolation of aerosol path reflectance into visible bands will result in apparent negative reflectance at visible wavelengths. The algorithm assumes that there is significant water leaving radiance, as detected by the Case II.S Turbid Water flag ATBD 2.5; note ATBD 2.6 should be read in conjunction with ATBD 2.5, and Appendix 1 Moore et al 199x. The algorithm partitions the top of the atmosphere reflectance into a component due to aerosols, and a component due to suspended particulate material (SPM) in the water. The SPM can be either of terrestrial (sediments) or biogenic (coccoliths) in origin.

3. Algorithm Description

3.1 Theoretical Description

3.1.1 Physics of the Problem

It is assumed that the algorithm is part of the processing chain for a Morel *et al* (ATBD 2.7) or Gordon and Wang (1994) type atmospheric correction. Data are assumed to have been screened for sun glint, land and clouds. The first stage of the AC algorithm (single scattering Rayleigh correction) generates $\rho_{rc}(\lambda) = \rho_a(\lambda)+\rho_{ra}(\lambda)+\rho_w(\lambda)$ (where $\rho_a(\lambda)+\rho_{ra}(\lambda)=\rho_{as}(\lambda)$). In Case I waters, $\rho_w(\lambda)$ is assumed to be zero for the NIR. In Case II.S waters, $\rho_w(NIR) \neq 0$, and it is necessary to estimate the values of $\rho_w(\lambda)$ and $\rho_{as}(\lambda)$.

In the NIR region (λ>700, <900nm) it is possible to use a single scattering model to estimate $\varepsilon(\lambda i,\lambda j)$. Conventionally a model using the Angstrom exponent is used:

$$\varepsilon(\lambda i,\lambda j)=[\lambda i/\lambda j]^{-n}$$

or $$\rho_{as}(i)=\rho_{as}(j)\,[\lambda i/\lambda j]^{-n}$$

However Gordon & Wang indicate that a log linear relationship provides a better fit:

$$\varepsilon(\lambda i,\lambda j)=\exp[c(\lambda i-\lambda j)]$$

or $$\rho_{as}(i)=\rho_{as}(j)\exp[c(\lambda i-\lambda j)]$$

implying that given $\rho_{as}(NIR)$ in any band and the empirical constant c , $\rho_{as}(NIR)$ can be determined for any other band.

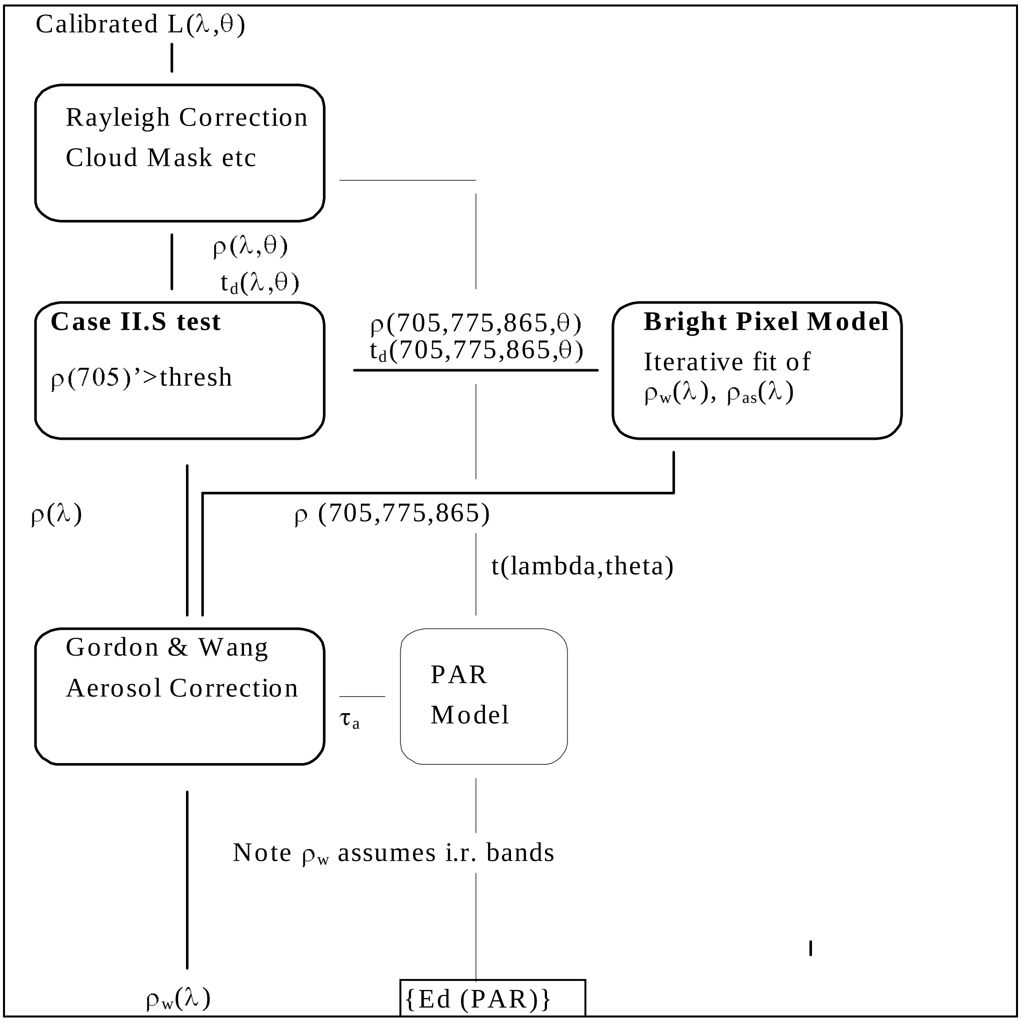
The wavelength range avoids major atmospheric absorption features. From aircraft and experimental observations of sediments it has been determined that for the NIR, ρ_w is constrained by a single parameter that is related to SPM load (see ATBD 2.5).

Given three bands, the parameters $\rho_{as}(NIR)$, $\rho_w(NIR)$ and c can be estimated. The resultant $\rho_{as}(NIR)$ is entered into the AC processing chain to determine aerosol type. $\rho_w(NIR)$ can be used to determine near surface SPM in the Case II.S waters.

3.1.2 Mathematical Description of Algorithm

The algorithm will use a lookup table of $\rho_W(\lambda,SPM,\theta,\theta_0,\Delta\varphi)$ generated for the MERIS scan angles and realistic sun angles. ρ_{as} and c are determined within the iterative procedure. The algorithm needs to correct $\rho_W(\lambda,SPM,\theta,\theta_0,\Delta\varphi)$ by the atmospheric transmission term $t(\lambda,\theta)$ derived as part of the AC algorithm. See Flow Chart, figure 1.

Figure 1 Atmospheric Component of Bright Pixel Processing (Bold indicates PML contribution).



For simplicity in the expression of the iterative method the angles have been compounded into a single term $\theta = [\theta v,\theta s,\Delta\phi]$; the superscript ^{R} is used to denote values in the LUTs and the superscript ^{e} is used to denote initial or intermediate estimates.
The LUT is accessed via the sediment IOP tables $a^R(SPM)$ and $b^R(SPM)$, i.e.
$\rho^R{}_{SPM}\,(SPM,\lambda,\theta) \equiv \rho^R{}_W(\lambda,a^R(SPM),b^R(SPM),\theta)$.
It should be noted that the LUTs include the absorption and scattering values for pure water, and the entries are denoted as a' and b'.

The inverse LUTs are $SPM^R(\lambda,\rho_w, \theta)$. The SPM estimates are obtained from the LUT of the reflectance ratio $\rho_w(865)/ \rho_w(775)$, $SPM^R(rr,\theta)$

The initial estimate required for the Newton-Raphson solution (Press et al, 1992) is obtained by an exact solution for the atmosphere / water leaving radiance. This solution assumes the value of $\varepsilon_{as}(775,865) = 1$, and that the relationship between $\rho_w(775)/\rho_w(865)$ is linear for a particular geometry. This slope is estimated for a SPM concentration of 5 mg l^{-1}; it has been shown with CASI imagery, that this estimate provides quite reasonable sediment maps over Case II waters.

Solution Method

1) Produce initial guesses $\rho_w(865)$ and $\rho_a(865)$ - See Appendix A

a) calculate slope at 5 mg.l^{-1} SPM.

$$k(775,865)=\rho^R{}_w(775,5,\theta)\times t_d(775,\theta)/\rho^R{}_w(865,5,\theta)\times t(865,\theta)-1.0$$

b) Solve for $\rho_w(865)$ at this SPM value

$$\rho^e{}_w(865) = \rho_{as}(865) \times(\varepsilon(775,865)- 1.0) /k(775,865)$$

or

$$\rho^e{}_w(865) = (\rho_{as}(775)- \rho_{as}(865)) /k(775,865)$$

c) Solve for ρ_a

$$\rho^e{}_a(865) = \rho_{as}(865) - \rho^e{}_w(865)$$

d) Determine initial estimate of SPM^e

$$SPM^e = \rho^e{}_w(865)\times a_w(865)/(0.0584 + b(SPM,865)/54.5) - a(SPM,865)x\rho^e{}_w(865)$$

Note, if the estimated value for SPM^e is negative the value should be set to zero.

2) The exact estimates of SPM and n are determined by solving the non-linear equations, using the Newton-Raphson method.

$$0 = (\rho_{as}(865)-\rho^R{}_w(865,SPM^e,\theta)-(\rho_{as}(775)-\rho^R{}_w(775,SPM^e,\theta)\times t(775,\theta))/ (775/865)^{-n}$$

$$0 = (\rho_{as}(865)-\rho^R{}_w(865,SPM^e,\theta)-(\rho_{as}(705)-\rho^R{}_w(705,SPM^e,\theta)\times t(705,\theta))/ (705/865)^{-n}$$

3) Fix the value of SPM retrieved in step 2 and solve the pair of linear equations for $\rho^e{}_{as}(865)$ and c.

$$0 = \rho_{as}(865)-\rho^R{}_w(865,SPM,\theta)\times t(\theta)-\rho^e{}_{as}(865)$$

$$0 = \rho_{as}(705)-\rho^R{}_w(705,SPM,\theta)\times t(\theta)-\rho^e{}_{as}(865)\times \exp(c\times(705-865))$$

4) Estimate

$$\rho^e{}_{as}(705) = \rho^e{}_{as}(865)\times \exp(c\times(705-865))$$

$$\rho^e{}_{as}(775) = \rho^e{}_{as}(865)\times \exp(c\times(775-865))$$

5) Return $\rho^e{}_a(775)$, $\rho^e{}_a(865)$for further processing by the multiple scattering model.

6) Estimate $\rho_w(510,SPM,\theta)$, for further processing in LPCM Model

3.1.3 Parameter Description

Symbol	Descriptive Name	I/O	Range/Reference/Remarks
t([705,775,865],θv,θs,Δϕ)	Atmospheric diffuse transmittance	i	From Rayleigh Correction
ρ_W(λ,SPM, θv,θs,Δϕ)	Water reflectance above surface	i	Database Lookup Table (SPM version) see text
ρ_W(λ,a',b', θv,θs,Δϕ)[1]	Water reflectance above surface	i	Database Lookup Table (IOP Version) see text
a(SPM)	Sediment absorption	i	Database Lookup Table
b(SPM)	Sediment backscatter	i	Database Lookup Table
c	Aerosol extrapolation parameter	-	Calculated internally
ρ_{as}([705,775,865],θv,θs,Δϕ)	Single scattering reflectance	i	From Rayleigh Correction
ρ_{as}([705,775,865],θv,θs,Δϕ)	Single scattering corrected reflectance	o	From Iterative Procedure
ε(705,865,θ)	ρ_{rc} Ratio	-	Calculated Internally
ε(775,865,θ)	ρ_{rc} Ratio	-	Calculated Internally
SPM	Sediment load	-	From procedure
θs	Solar Zenith angle	i	From Navigation
Δϕ	Azimuth Difference	i	From Navigation
θv	Viewing Angle	i	From Navigation
θ ≡ [θv,θs,Δϕ]	View / Solar angle	-	Naming Convention

1 The a' and b' indicate that the tables are offset by a_w, b_w

3.1.4 Error Budget Estimates

TBD

3.1.5 Practical Considerations

The algorithm requires lookup tables.

3.1.6 Sensitivity to IOPs of sediments

A. Sensitivity to variations in Backscatter

Both algorithms 2.6 and 2.11 depend on the IOPs of sediment. The parameterisation of reflectance for waters dominated by suspended material involve knowledge of three IOPs and their spectral properties: the sediment specific absorption a(SPM,λ); the specific scattering b(SPM,λ) and the backscatter ratio . $\tilde{b}$ The sensitivity of these IOPs with regard to sediment type has been investigated using measurements of reflectance with a spectroradiometer under laboratory conditions using a tank of depth 2m (Bale *et al.*, 1994). These measurements are acceptable, due to the high optical attenuation of pure water at NIR wavelengths (1.53 m^{-1} at 700 nm, 0.20 m^{-1} at 865 nm).

In order to evaluate the effects of sediment type the reciprocal of remote sensed reflectance has been used, since this should be linear with sediment load.
The remote sensed reflectance is expressed as:

$$Rrs = \left[\frac{(1-\rho)(1-\tilde{\rho})}{n_w{}^2}\right]\frac{1}{Q}\left[\frac{R}{(1-rR)}\right] = I\frac{1}{Q}\left[\frac{R}{(1-rR)}\right]$$

where n_w is the refractive index of seawater, R is the irradiance reflectance, ρ is the Fresnel reflectance at normal incidence, $\tilde{\rho}$ is the Fresnel reflectance for sun and sky irradiance, r is the air-water reflectance for diffuse irradiance, and Q is the ratio of upwelling irradiance to radiance.
The reciprocal of the remote sensed reflectance is thus:

$$\frac{1}{Rrs} = \left[\frac{Q}{I}\right]\left[\frac{1}{R} - r\right]$$

For NIR wavelengths, where b_w is assumed to approximate to zero, and the only optically active component is SPM, the reciprocal of remote sensed reflectance can be expressed as:

$$\frac{1}{Rrs} = \left[\frac{Q}{I}\right]\left[\frac{a_w + a_s[SPM]}{fb_{bs}[SPM]}\right]$$

or :

$$\frac{1}{Rrs} = \underbrace{\left[\frac{Q}{If}\right]\left[\frac{a_s}{b_{bs}} - fr\right]}_{Intercept} + \underbrace{\left[\frac{Q}{If}\right]\left[\frac{a_w}{b_{bs}}\right]}_{Slope}\frac{1}{[SPM]}$$

The intercept is an extrapolation to infinite sediment and does not have a physical meaning; however the slope indicates that for moderate sediment the relationship is locally linear with the exact slope depending on the sediment specific backscatter (b_{bs}). Figure 6.a shows the relationship for a number of sites along the Humber estuary; these sites show variability of the slope, and hence the sediment specific backscatter.
The turbid water relies on the relationship between bands rather than the absolute value of SPM. For two bands the linear equations above can be solved giving a slope:

$$\left[\frac{I(\lambda_2)f(\lambda_2)Q(\lambda_1)}{I(\lambda_1)f(\lambda_1)Q(\lambda_1)}\right]\left[\frac{b_{bs}(\lambda_2)}{b_{bs}(\lambda_1)}\right]\left[\frac{a_w(\lambda_1)}{a_w(\lambda_2)}\right] \cong \left[\frac{a_w(\lambda_1)}{a_w(\lambda_2)}\right]$$

and an intercept:

$$\left[\frac{Q(\lambda_1)}{I(\lambda_1)f(\lambda_1)}\right]\left[\frac{a_s(\lambda_1)}{b_{bs}(\lambda_1)} - rf(\lambda_1) - \frac{a_w(\lambda_1)}{a_w(\lambda_2)}\left\{\frac{a_s(\lambda_2)}{b_{bs}(\lambda_2)} - \frac{b_{bs}(\lambda_1)}{b_{bs}(\lambda_2)}rf(\lambda_2)\right\}\right]$$

As above the intercept in physically unrealistic; however the slope is dependent on the relative absorption of pure water in the two bands. Figure 6.b show the relationship between the reciprocal of reflectance in the 775nm and 865nm for the same data as in figure 6.a.; it can be seen that the points converge to a common line with a slope of 0.579, close to the expected ratio of $a_w(\lambda_1)$: $a_w(\lambda_2)$ of 0.595 in the two bands

These results show that although the exact value of SPM iterated within the turbid water correction procedure may vary according to sediment properties, the relationships between the remote sensed reflectances are robust and independent of sediment type.

B. IOPs determined from experimental observations

Figure 2 shows the effect on the $\rho_w(775)/\rho_w(865)$ vs. SPM relationship, for different values b(SPM), with a constant value of a(SPM) = 0.02 m^{-1} (chosen from literature, inversion of tank reflectance experiments and by considering anomalous diffraction theory). The b(SPM) has little effect on the reflectance ratio over two decades of change; the value of 1.0 m^{-1} gives better estimates at low SPM

Fig 2. ρ(775)/ρ(865) vs. SPM for a constant a(SPM) of 0.02 and a range of b(SPM)

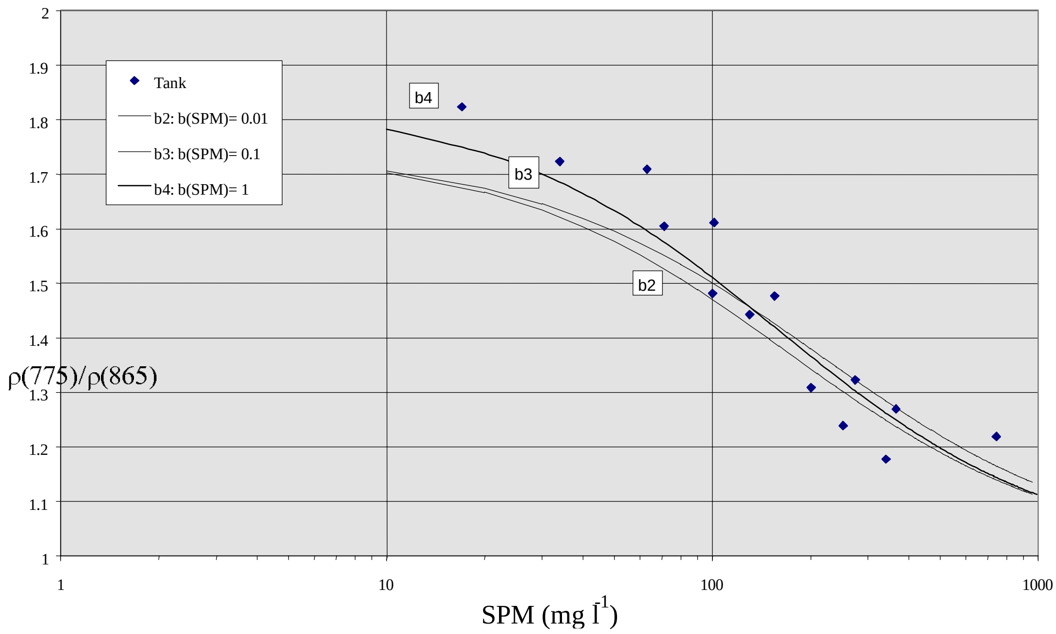


Fig 3. ρ(775)/ρ(865) vs. SPM for a constant b^1(SPM) of 0.5 and a range of a^1(SPM)

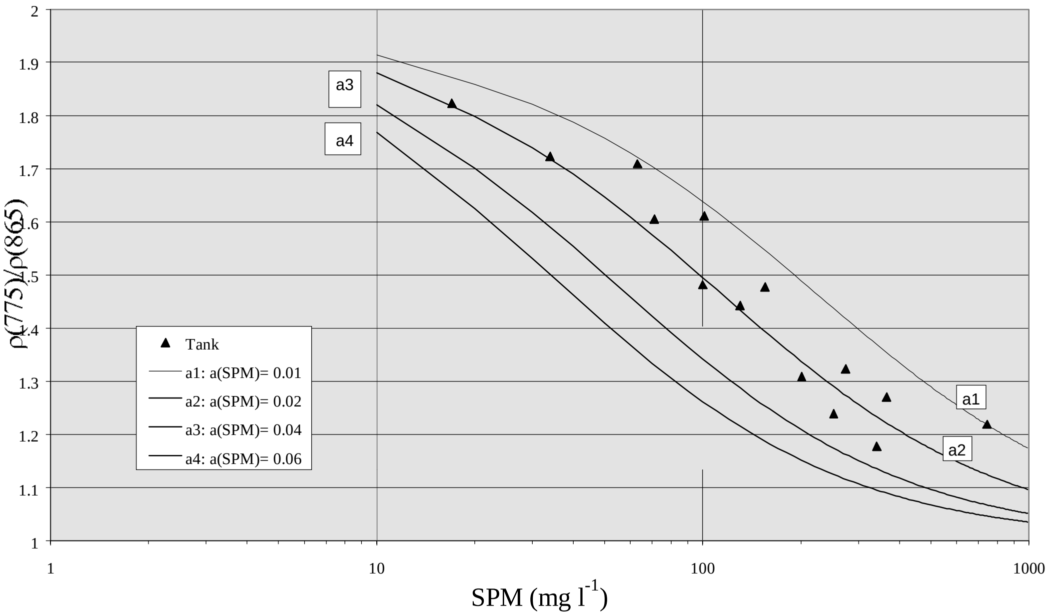


Figure 3 shows the effect of varying a(SPM) on the $\rho_w(775)/\rho_w(865)$ to SPM relationship. Compared with the effect of b(SPM), the ratio is highly sensitive to small changes of a(SPM) around the test value of 0.02 m^{-1}. The a(SPM) = 0.02 m^{-1} line fits the observed data best, with the range 0.01 to 0.03 m^{-1} bracketing the full data range.

The scattering coefficient is expected to change with a λ^{-1} spectral dependence, which would imply that b(SPM,775) ≅ 1.1×b(SPM,865). Figure 4 shows the effect of varying the spectral dependence of scattering, by adjusting the '1.1' factor and shows that there is little evidence of spectral variation in b(SPM). These analyses confirm that a fixed value of a(SPM) = 0.02 m^{-1} is justified. Thus the model to derive SPM (ATBD 2.11) and to estimate aerosol reflectance is fixed with b(SPM) = 2.0 m^{-1}, and a(SPM) = 0.02 m^{-1}, with no spectral variation.

Figure 4. Variation in ρ(775)/ρ(865) vs. SPM for a range of spectral dependency of ρ(775)/ρ(865)

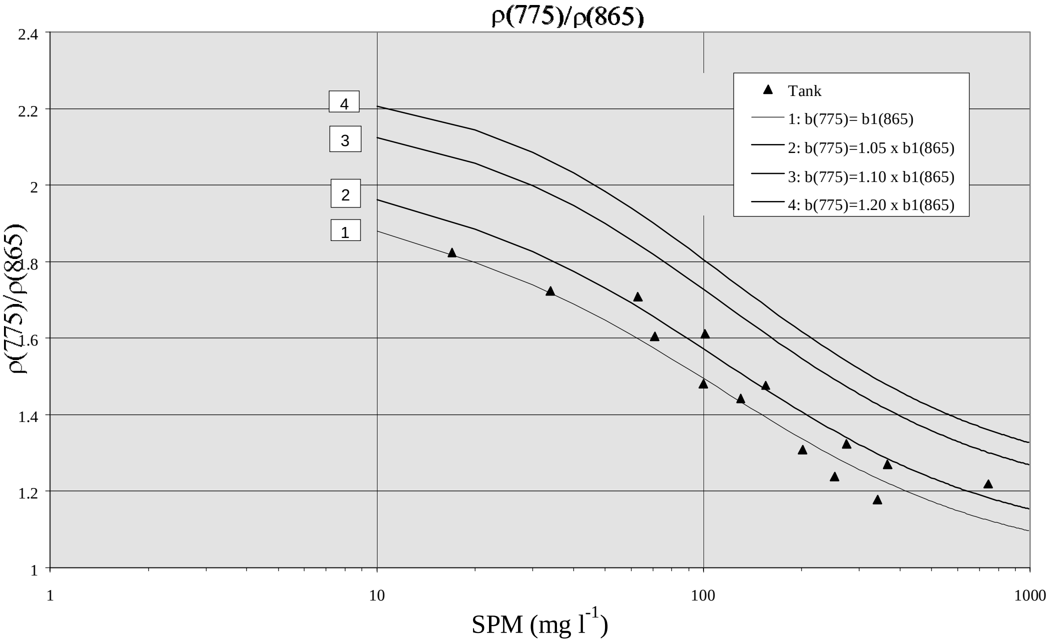


Figure 5 shows the dependence of ρ(865) on b(SPM) for fixed value a(SPM).= 0.02 m^{-1}. The best fit is for b(SPM,865) = 2 m^{-1}. This figure although high, matches the fine sediments likely to be in suspension in the majority of shelf seas.

Figure 5. ρ(865) vs. SPM for theoretical ρ(865) and a range of b (SPM)

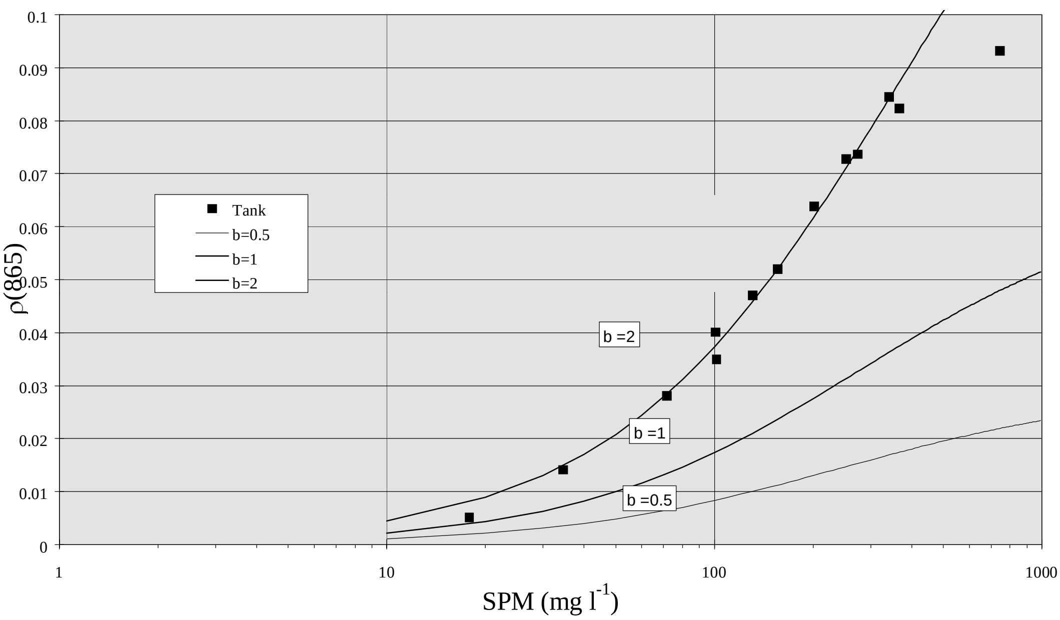
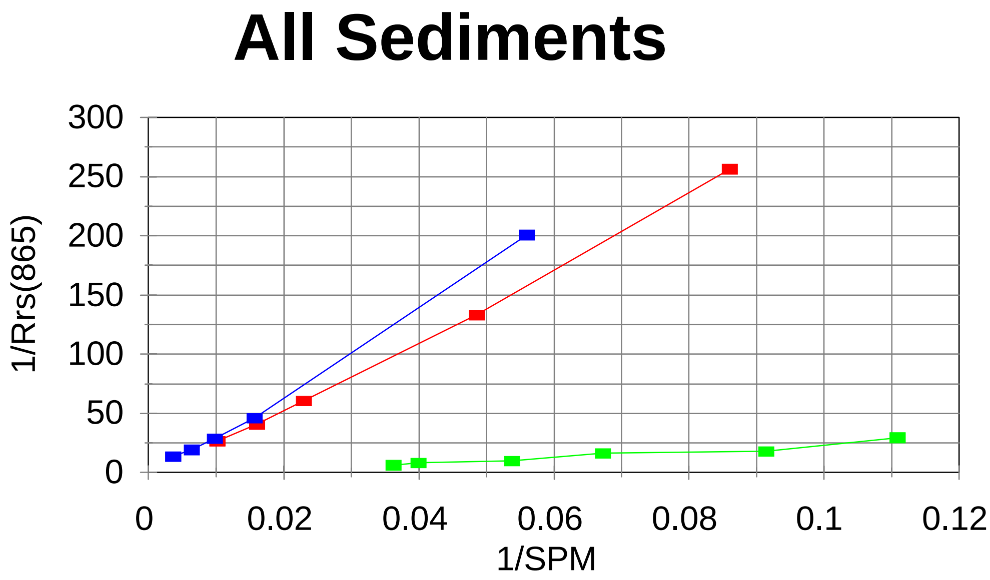
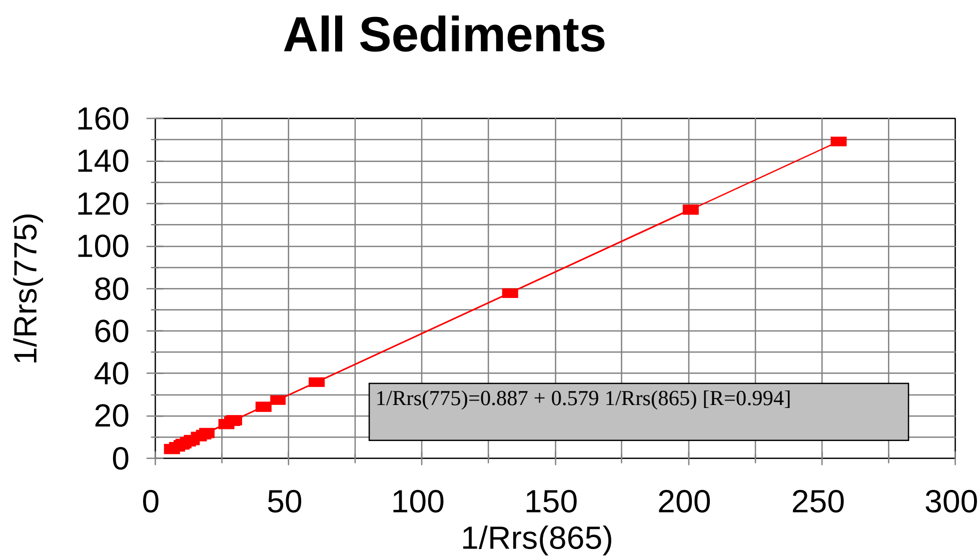


Figure 6. (a) The relationship between the reciprocal of remote sensed reflectance at 865nm vs. the reciprocal of sediment load. The lines represent three sediments types found along the Humber estuary. (b) the relationship between the reciprocal of remote sensed reflectance at 775nm and 865nm; the data is same as (a).

a.



b.



3.2 Practical Considerations

3.2.1 Calibration and Validation

The method has been validated using aircraft imagery, and further validation is anticipated using the MOS, OCTS and SeaWiFS sensors when they become available.

3.2.2 Quality Control and Diagnostics.

Certain very high sediment waters, or extreme atmosphere type could return anomalous results. Both of these would be classified as cloud / land because of their high absolute reflectance.

3.2.3 Exception Handling

Potentially the iterative solution can produce either infinite or negative reflectances. This event should be trapped as an atmospheric correction failure. In practice this has not happened with a large test set of CASI aircraft imagery (more than 100 512x5000 images).

3.2.4 Output Product

Atmospheric reflectance in NIR

4. Assumptions and Limitations

The algorithm needs to be tested on a range of simulated data with extreme aerosol types.

5. References

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SUMMARY SHEET

Product Name: Case II.S (Sediment) Bright Water Correction
Product Code: Internal to ocean atmospheric correction.
Product Level: 2

Product Parameters:

Coverage	Coastal Waters and Oceanic Coccolithophore Blooms
Packaging	
Units	---
Range	---
Sampling	---
Resolution	Any
Accuracy	Estimates from tests with CASI data indicate that the accuracy is within the radiometric calibration of CASI (±5%)
Geo.-Location Requirements	Angle of View
Format	Internal I/O
Appended Data	
Frequency Of Generation	As Atmospheric Correction
Size of Product	

Additional Information

Identification of Bands	[705,775,865]
Assumptions on MERIS Input Data	Rayleigh Corrected with atmospheric transmission
Output Data	ρ_{as}[705,775,865]
Identification of Ancillary and Auxiliary Data	
Assumptions of Ancillary and Auxiliary Data	

Appendix A

Initial Estimates of ρ_a and ρ_w

In waters dominated by sediments the single scattering aerosol path reflectance calculated by Rayleigh correction ($\rho_{rc}(\lambda)$) is a composite of the water reflectance and the aerosol reflectance i.e.:

$$\rho_{rc}(\lambda) = \rho_{as}(\lambda)+t_d(\lambda)\times\rho_w(\lambda)$$

For simplicity, interaction terms (e.g. $\rho_{rs}(\lambda)$) are ignored but propagate forward with $\rho_{as}(\lambda)$
For the two bands used in the turbid water atmospheric correction the reflectance can be represented as follows.

$$\rho_{rc}(775) = \rho_{as}(865)\times\varepsilon_{as}(775,865)+ \varepsilon_w(775,865)\times\rho_w(865)$$

$$\rho_{rc}(865) = \rho_{as}(865) + \rho_w(865)$$

where ε_w represents the spectral reflectance ratio for water and accounts for the diffuse transmission of the atmosphere.

By substitution these equations can be solved to give $\rho_W(865)$ in terms of the observed reflectances and the epsilons:

$$\rho_w(865) = (\rho_{rc}(775) - \varepsilon_{as}(775,865)\times \rho_{rc}(865))/(\varepsilon_w(775,865)- \varepsilon_{as}(775,865))$$

The only unknowns are ε_{as} , and ε_w. The angstrom exponent for continental aerosols is unlikely to exceed 2.0 and is more usually around 1.2. This gives an ε in the range 1.14 to 1.25. The ε_w is determined by the scattering of the particulates and the absorption of water. At low SPM levels, and a non absorbing particulate, ε_w approximates to the ratio of $a_w(775)/a_w(865)$. This value is 1.76 and much greater than the ε.

The initial estimates are based on the assumption that ε is 1 and that ε_w is set for a SPM load of 5 mg.l^{-1}.

Sensitivity tests indicate that the use of a simple algorithm is as efficient as the LUT procedure.

The initial estimate of SPM is calculated as:

$$SPM^e = \rho^e_W(865)\times a_W(865)/(0.0584 + b(SPM,865)/54.5) - a(SPM,865)x\rho^e_W(865)$$

where $a_W(865) = 4.45$; $b(SPM,865) = 2$; $a(SPM,865) = 0.02$