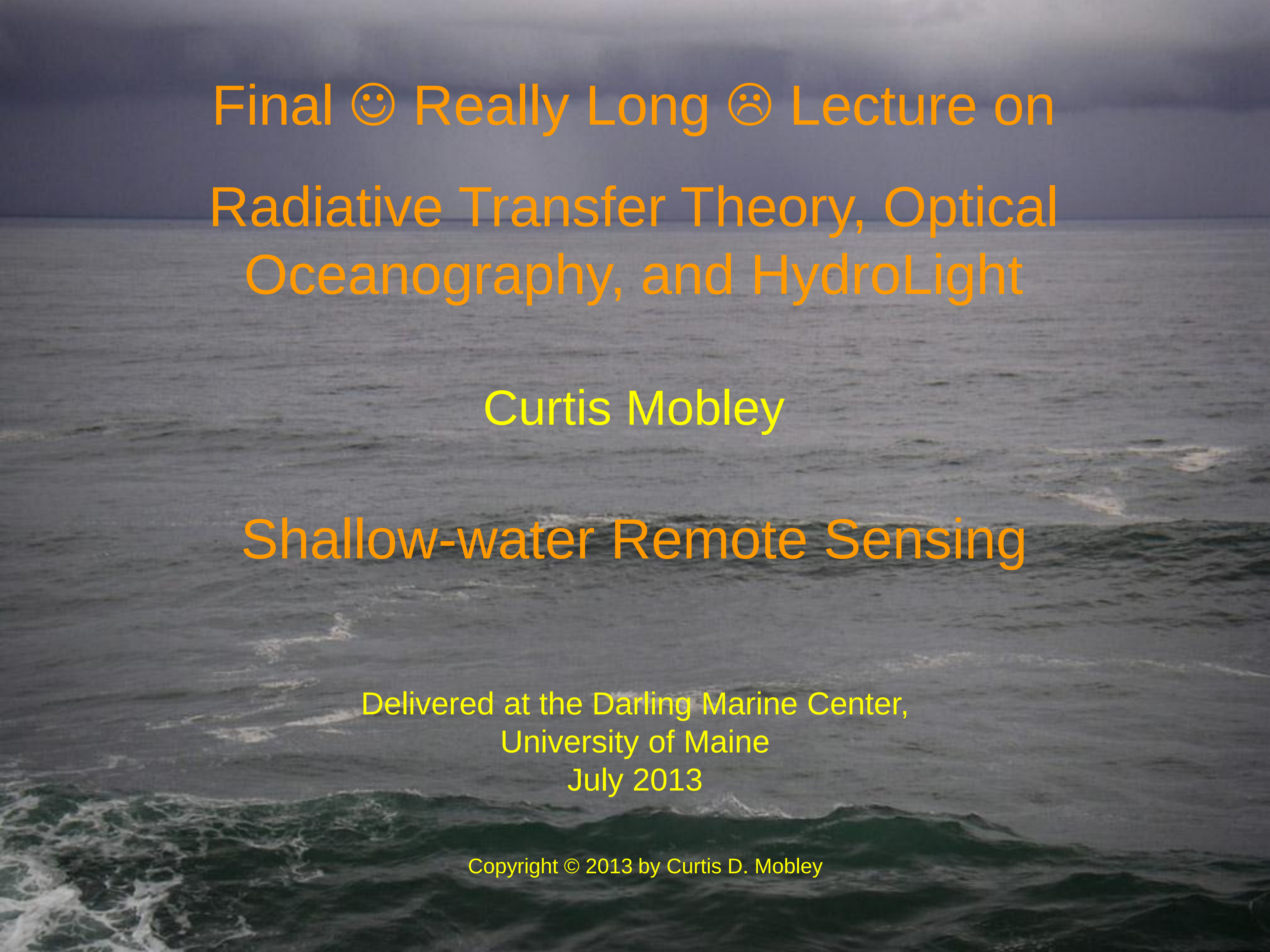


Final ☺ Really Long ☹ Lecture on

Radiative Transfer Theory, Optical Oceanography, and HydroLight

Curtis Mobley

Shallow-water Remote Sensing

Delivered at the Darling Marine Center,
University of Maine
July 2013

Who Cares About Shallow Waters?

- Military needs maps of bathymetry and bottom classification in denied-access areas for amphibious operations; water clarity maps for optical mine finding and diver operations

- Ecosystem managers need to map and monitor bottom type and water quality for management of coral reefs, sea grass beds, kelp forests, fisheries, and recreation
  - episodic (hurricane effects, harmful algal blooms, pollution events)
  - long-term (global climate change, anthropogenic changes from coastal land usage)

- Maps needed at 1-10 meter spatial scales (not kilometers), and sometimes within ~1 day of image acquisition

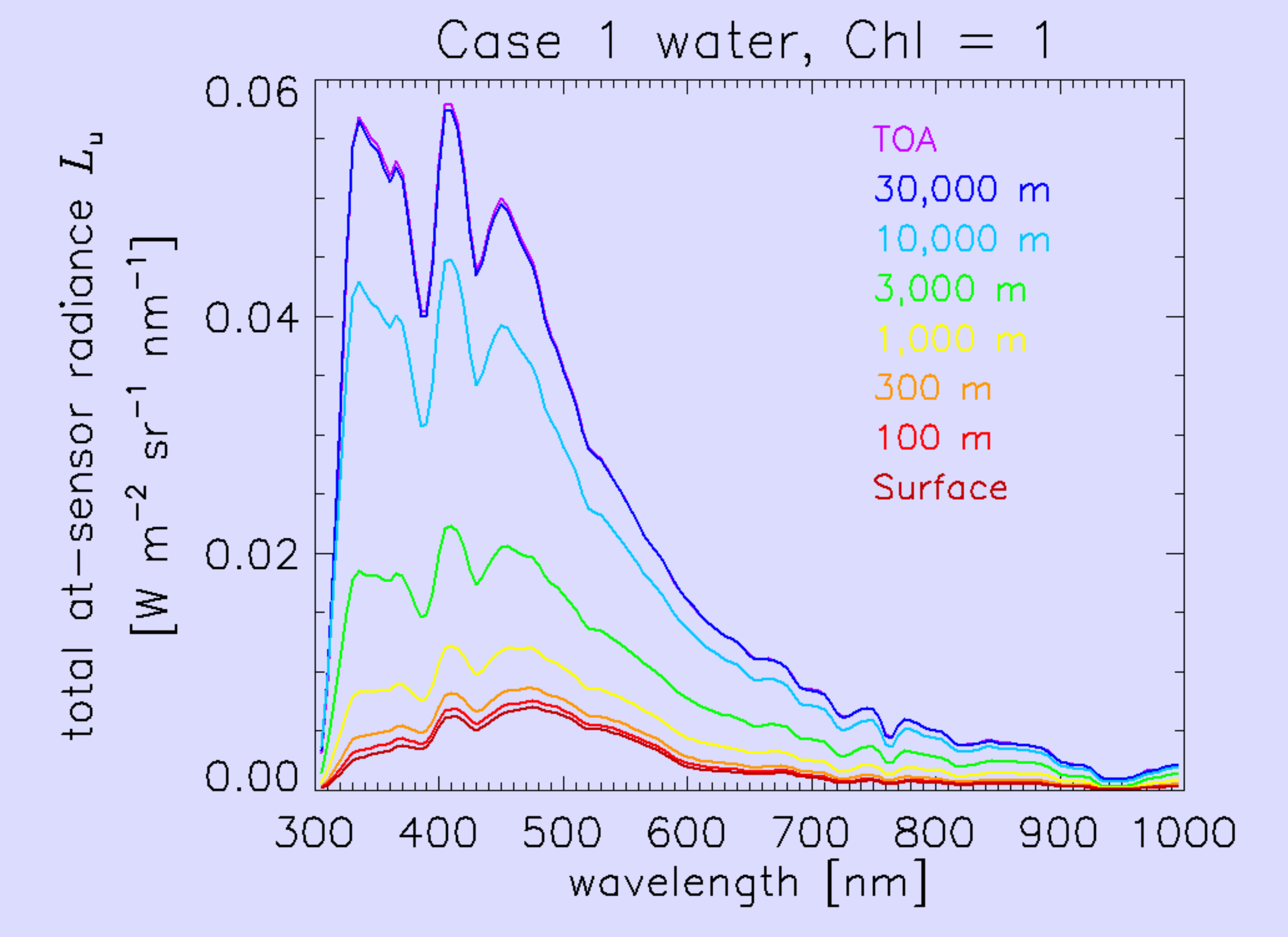
A New Set of Problems

- Need new atmospheric correction techniques for shallow and case 2 waters where the black pixel assumption fails, and for coastal atmospheres with absorbing aerosols

- Need new retrieval algorithms, e.g. for bottom depth and bottom type. Statistical algorithms often fail in coastal waters (complex mixtures of phytoplankton, minerals, dissolved substances) and optically shallow waters (bottom-reflectance effects) and have nonuniqueness problems

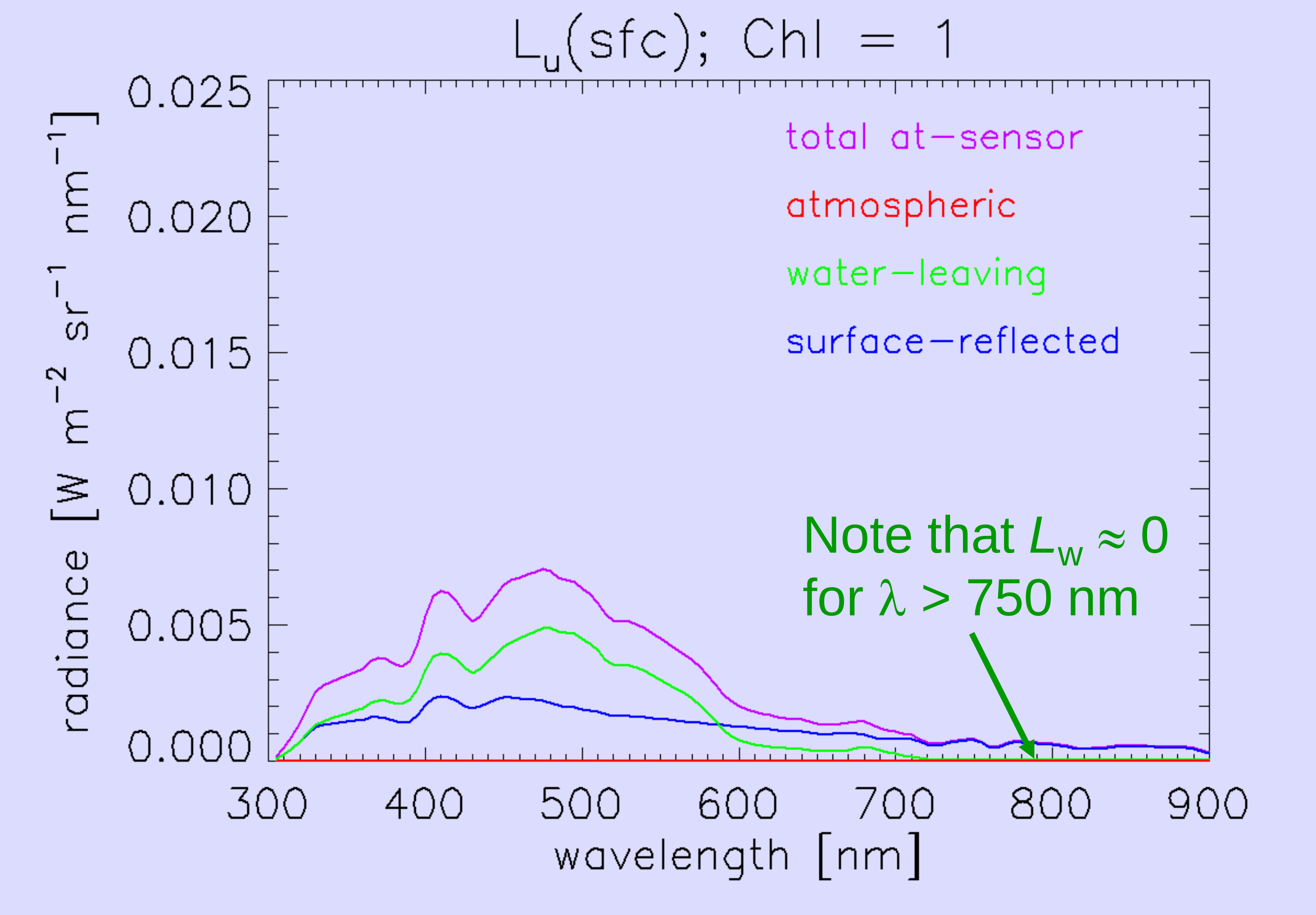
Total At-sensor Radiances at Various Altitudes

Most airborne remote sensing is done from altitudes of 1,000 to 10,000 m. Atmospheric path radiance is very important.



Remember L_w(NIR) ≈ 0 in Case 1 Water

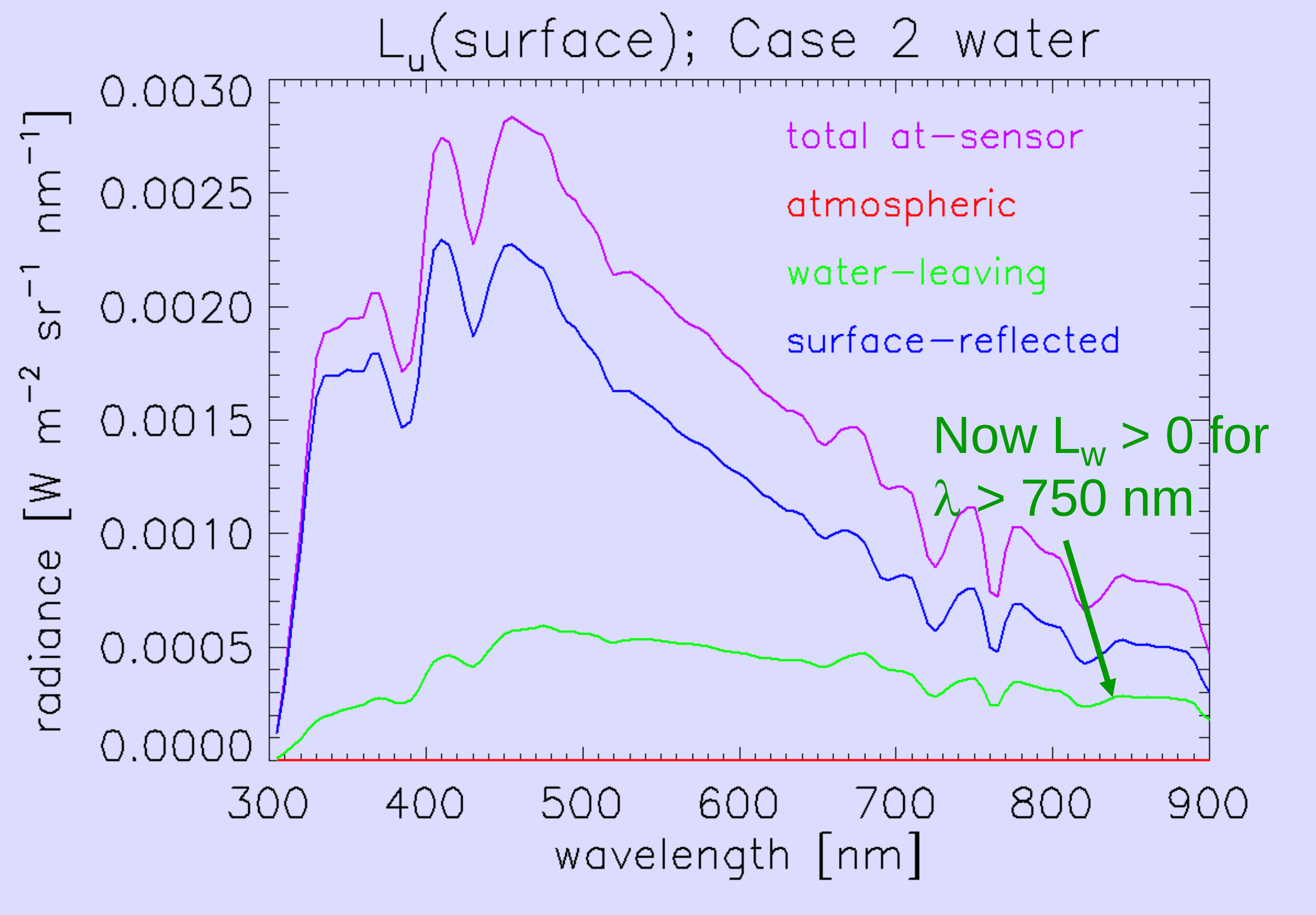
Upwelling (nadir-viewing) radiances just above the sea surface



Note that $L_w \approx 0$ for $\lambda > 750$ nm

L_w(NIR) > 0 in Case 2 or Shallow Water

Upwelling (nadir-viewing) radiances just above the sea surface

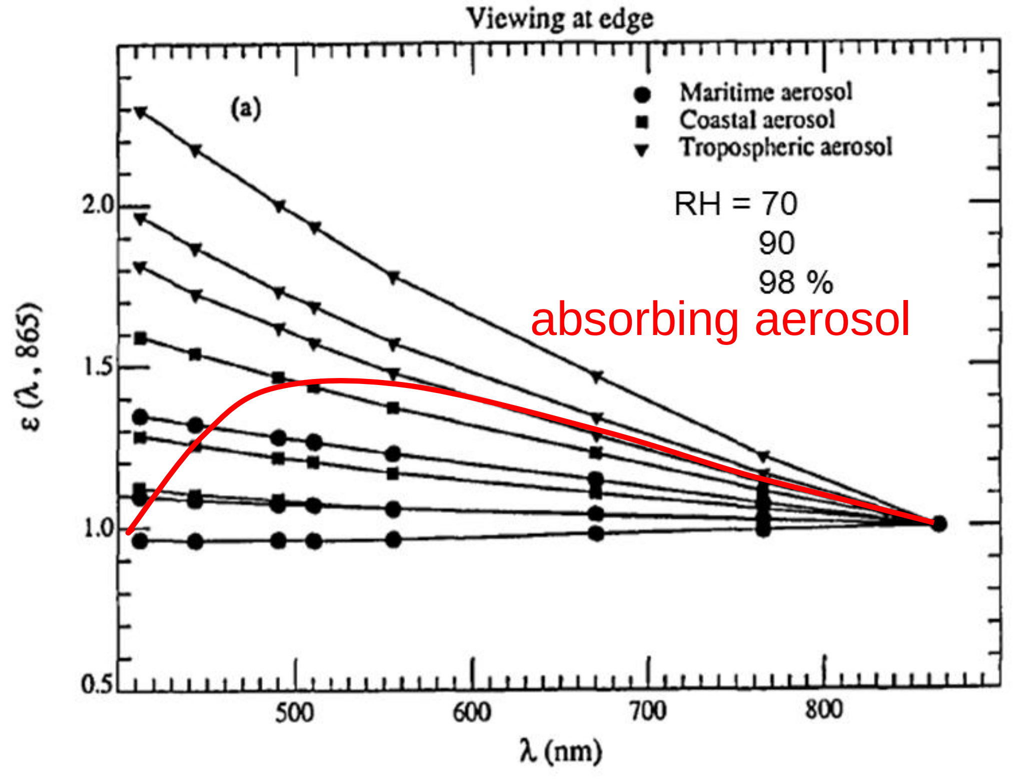


Now $L_w > 0$ for $\lambda > 750$ nm

The black pixel assumption may not be valid in shallow or Case 2 water

“Black Pixel” and Extrapolation

$R_{rs}(\lambda) = \varepsilon(\lambda, \lambda_o)\, R_{rs}(\lambda_o)$



Even if the black pixel assumption is good, strongly absorbing (usually in the blue) aerosols lead to subtracting too much aerosol contribution, and you can end up with negative R_{rs} near 400 nm.

black curves are for spherical, non-absorbing aerosols

Requirements for Case 2 or Shallow Water Atmospheric Ccorrection

We need to have an atmospheric correction technique that

- works for any water body (Case 1 or 2, deep or shallow)
- works for any atmosphere (including absorbing aerosols, which are common in coastal areas)
- does not require zero water-leaving radiance at particular wavelengths (no “black pixel” assumption)

Atm Corr 1: Empirical Line Fit (ELF)

The essence of the ELF technique is to

- Make field measurements of the remote-sensing reflectance $R_{rs}(\lambda)$ at the same time as the image acquisition.

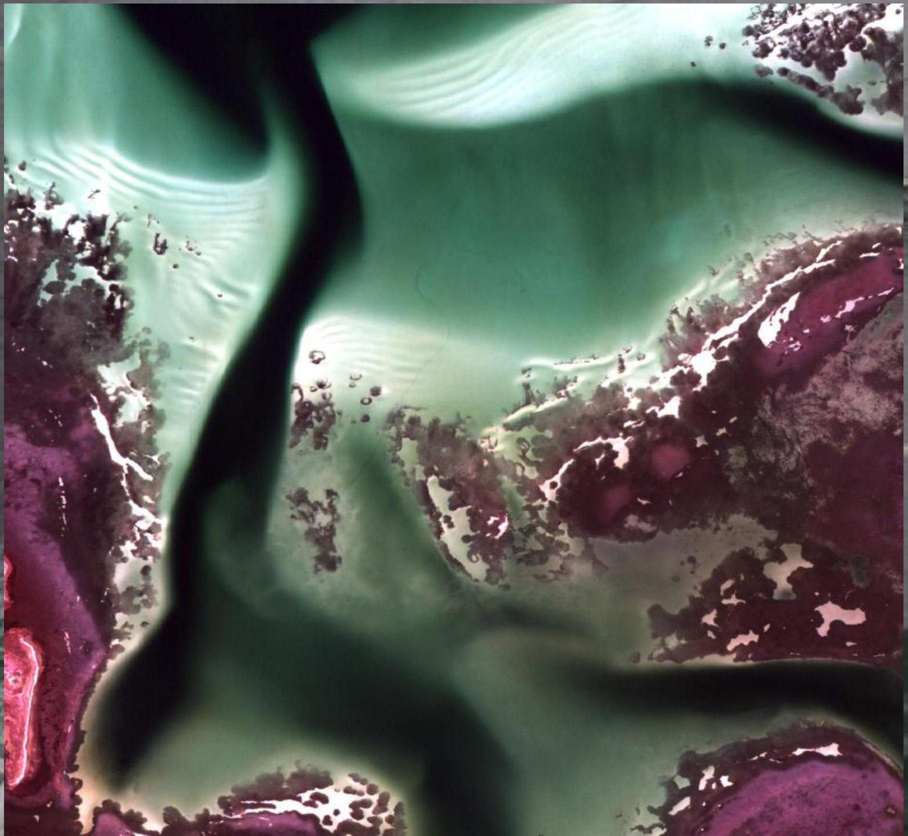
- R_{rs} measurements at various points in the image can then be correlated with the at-sensor measurements in digital counts (or any other sensor engineering units). Get a different correlation function for each wavelength.

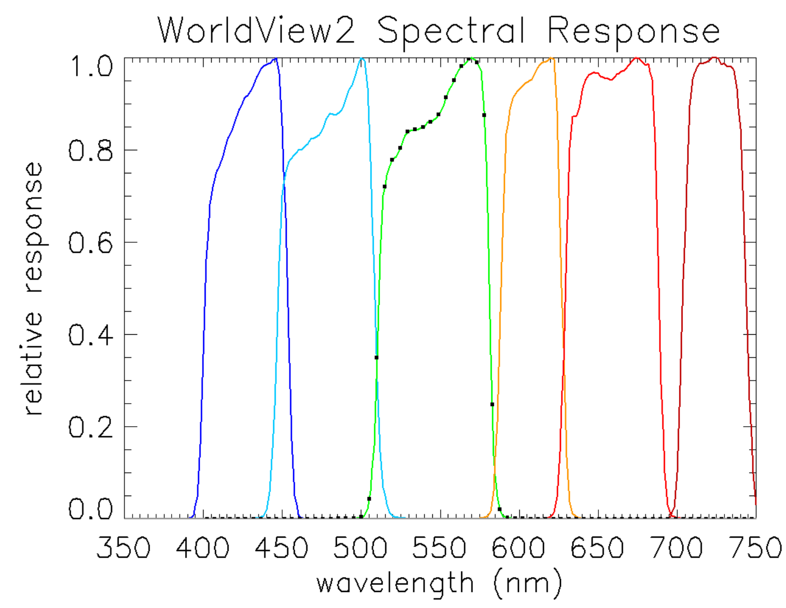
- Assume that the atmosphere, solar illumination, and surface wave conditions are the same for every pixel of the entire image.

- Use the ELF function to convert at-sensor L_u or digital counts to sea-level R_{rs} for each pixel in the image.

ELF Example

DigitalGlobe WorldView-2 (8 band, multispectral) satellite imagery of St. Joseph’s Bay, Florida, USA.
www.digitalglobe.com/about-us/content-collection#overview
DG sells high-spatial resolution (0.5-2 m) imagery of TOA digital counts & TOA radiances without any atmospheric correction (no longer true?)

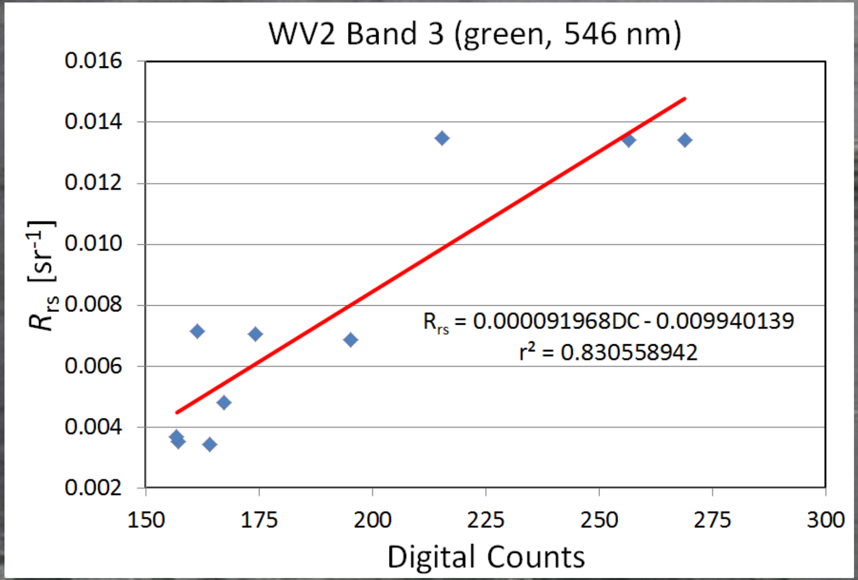


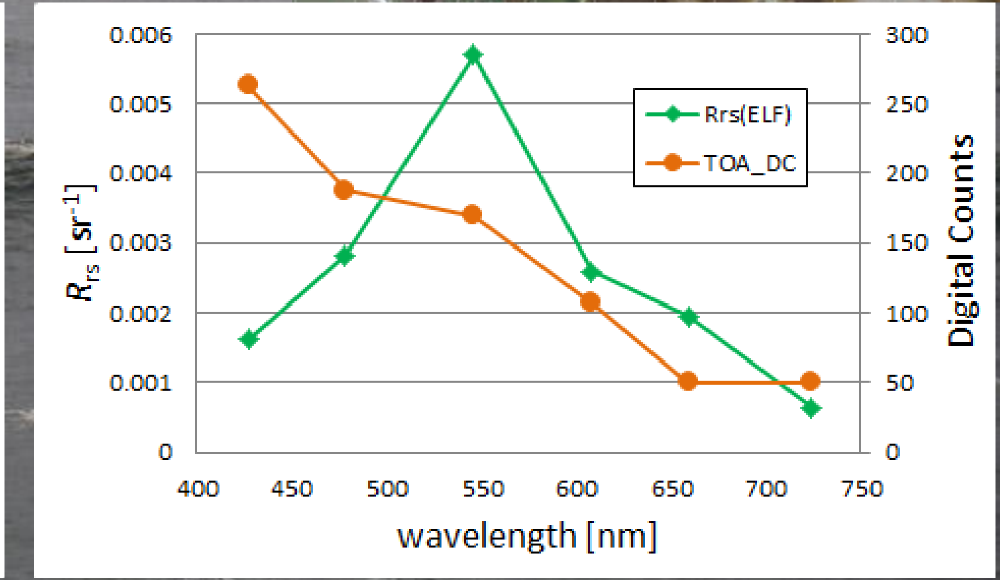


RGB generated from WV2 bands 5, 3, and 2 (or 656, 546, and 478 nm for red, green, and blue).
This area is about 6.3 km^2 (1400 × 1297 pixels)

ELF Example

$R_{rs}(\lambda)$ was measured from a small boat at 10 locations in the image





R_{rs}(546 nm) for 10 ground stations vs TOA digital counts for the image pixels of the same locations.

Example conversion of TOA digital counts to $R_{rs}(\lambda)$ for one image pixel.

ELF Summary

✓ The ELF functions account for atmospheric path radiance for any atmospheric conditions, without the need for knowledge of what those conditions are. No atmospheric measurements are needed.

✓ The technique works for optically shallow or case 2 water, for which R_{rs} may not approach zero in the near-IR. No “black pixel” assumption is needed.

✓ The technique works for any sun and sensor geometry, or sensor altitude (airborne or satellite)

X ELF requires field measurements of R_{rs} to be made at the time of image acquisition, which is labor intensive and may be impossible in some locations.

X A set of ELFs is valid only for one image and cannot be applied to a different area or to different images of the same area, because the atmospheric and water conditions (or bottom depth) will differ for other locations and times.

X The same ELF is applied to all pixels in the image, even though different parts of the image may have different atmospheric conditions and different viewing geometries. (In the case of airborne sensors, the viewing geometry and atmospheric path lengths from sensor to surface can vary greatly for different image pixels.)

Atm Corr 2: Radiative Transfer Techniques

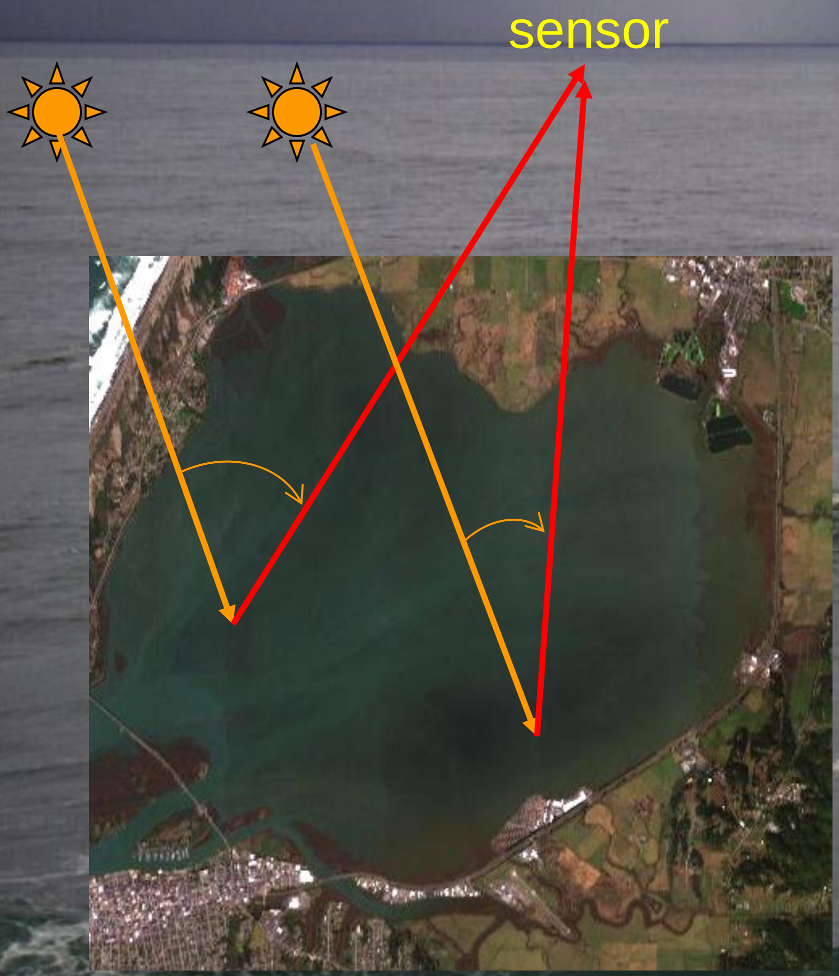
If we know the inherent optical properties of the atmosphere, then we can use an atmospheric radiative transfer (RT) model to compute the atmospheric path radiance contribution to the measured total, and subtract it out to obtain the water-leaving radiance.

Example: The TAFKAA RT model was developed by the US Navy for this purpose and is used by many research groups (see the TAFKAA references in the papers directory; TAFKAA = The Algorithm Formerly Known As ATREM; ATmospheric REMoval).

TAFKAA has been used to create large look-up tables for various wind speeds, sun angles, viewing directions, and atmospheric properties (aerosols, surface pressure, humidity, etc). These calculations required ~6 x 10^7 RT simulations with TAFKAA, taking several months of time on a 256 processor SGI supercomputer.

TAFKAA User’s Guide, 2002

Radiative Transfer Techniques



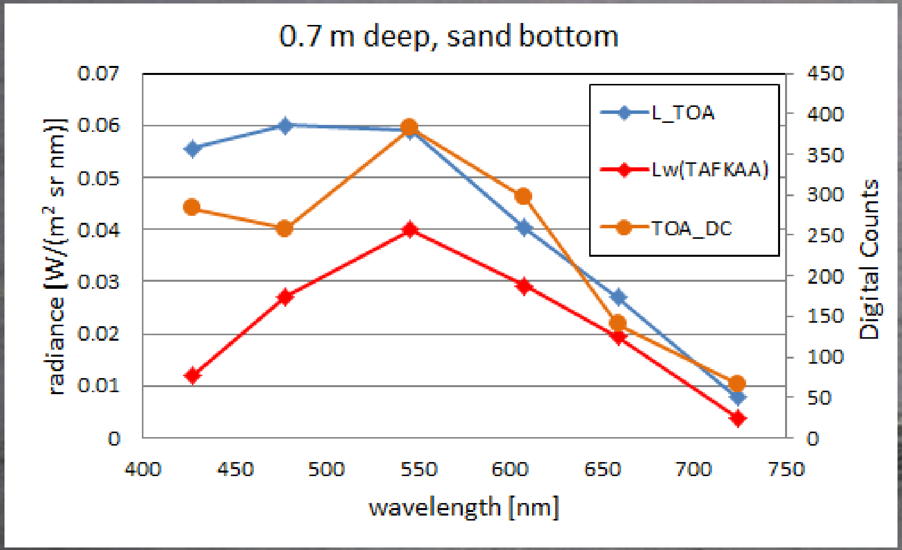
Main advantage: Each pixel in the scene has a different viewing geometry, and thus gets a different correction.

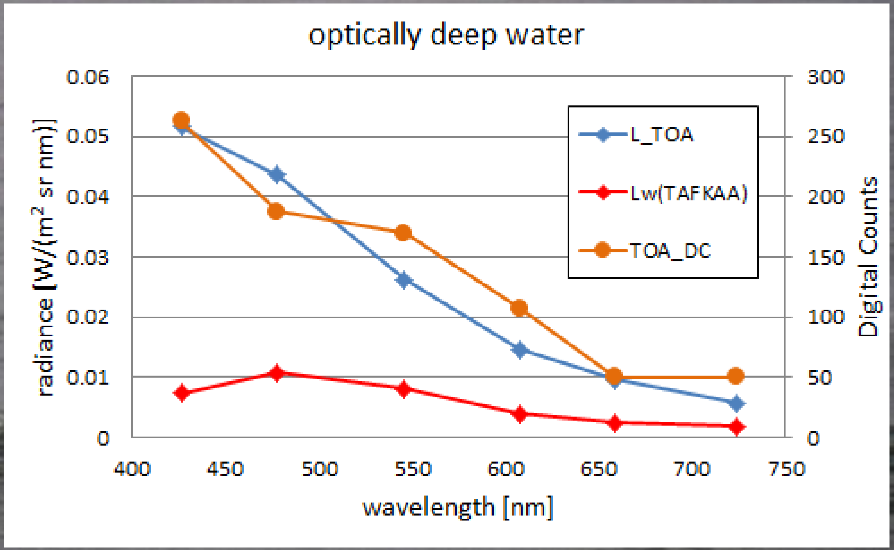
Main disadvantage of any RT method is that it requires measurement or estimation of the atmospheric properties.

This also requires having someone in the the field making meteorological measurements, or the use of atmospheric prediction models.

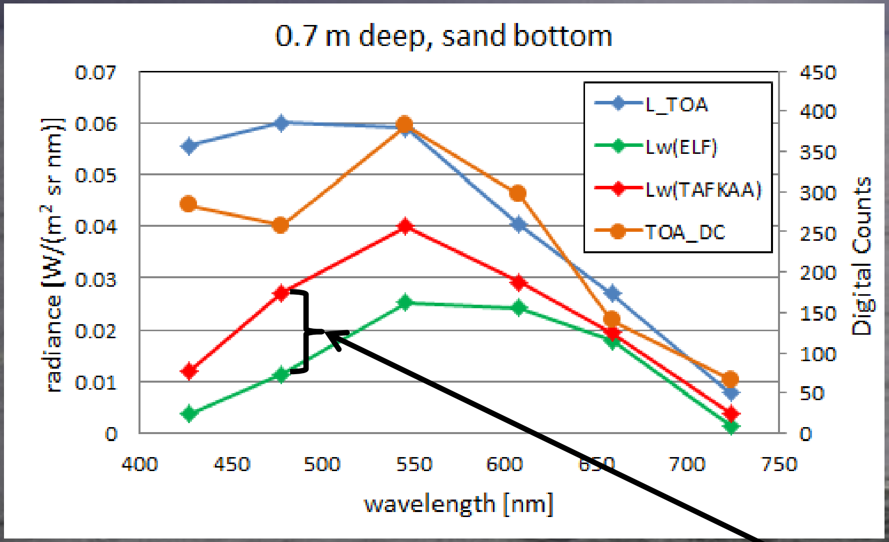
TAFKAA WV2 Example

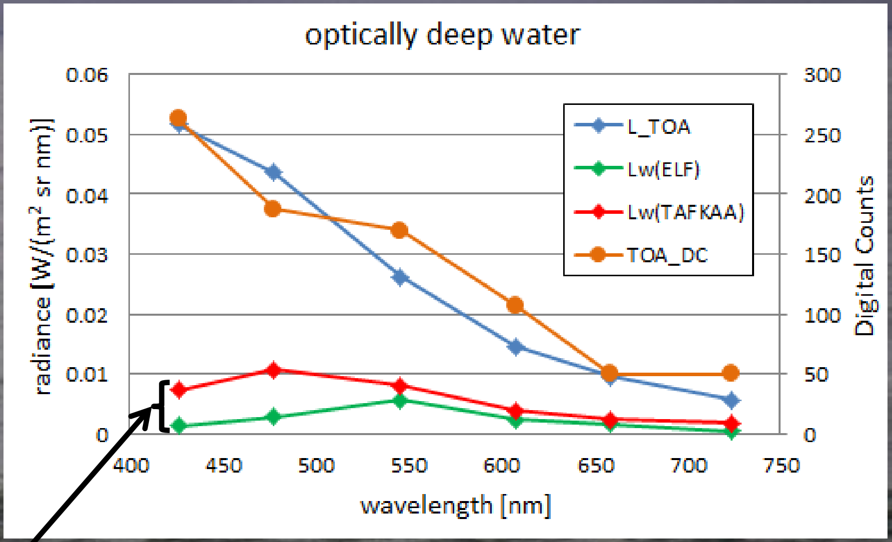
Two WV2 pixels corrected by the TAFKAA RT model





TAFKAA vs ELF





TAFKAA and ELF corrections applied to the same WV2 image pixels differed by as much as a factor or 5 at 427 nm. This makes a HUGE difference in retrieved values of bottom depth, Chl, etc.

Which correction is correct? Probably neither one!!

TAFKAA vs ELF

Why the difference in ELF and TAFKAA in this example?

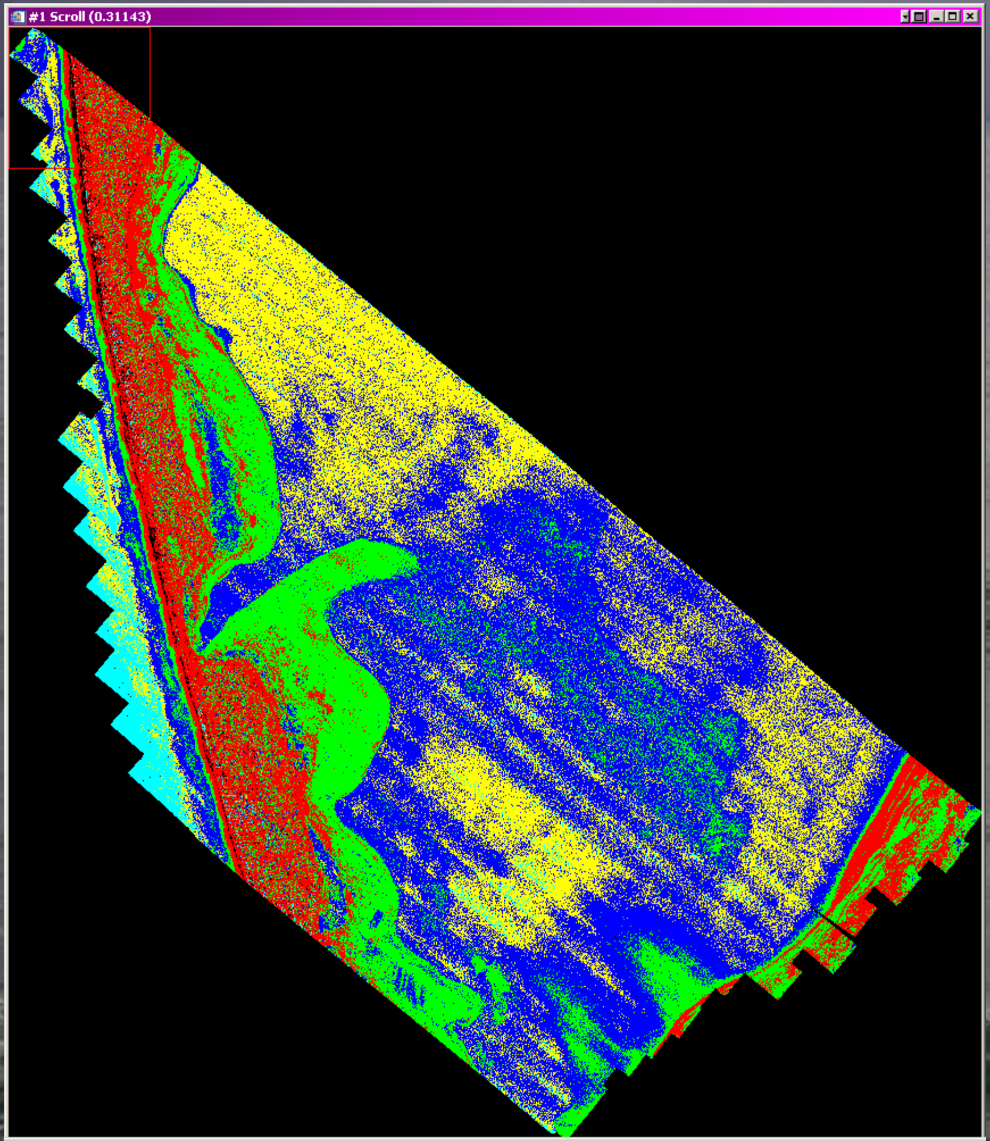
ELF: The ground measurements of R_{rs} were made over a period of a week before the image acquisition. The atmospheric conditions, water IOPs, and water depths (due to tides) were probably different for each station (on different days), and different from the time of the image.

TAFKAA: There were no measurements of atmospheric conditions at the time of the image. Therefore, TAFKAA was run with “best guesses” (standard mid-latitude atmospheric conditions), which were probably wrong.

Measurements MUST be made simultaneously with the image.

In this example, the image was simply not useful because we did not have the ancillary measurements needed to get a good atmospheric correction.

Imperfect Atmospheric Correction Effects on Bathymetry



Effects of imperfect atmospheric correction on retrieved (by spectrum matching) bathymetry. The overall pattern is correct but note the “striping” in retrieved depths.

1 m contours (RGBYC =1-5 m)

courtesy of P. Bissett, FERI

Atmospheric Correction Techniques

The ELF technique can give good results for any atmospheric conditions and does not require aerosol modeling, extrapolation, or zero water-leaving radiances. The estimation of R_{rs} is easy to do with inexpensive instruments. It is therefore widely used for coastal remote sensing when R_{rs} measurements can be obtained.

The disadvantage is that it requires surface radiance measurements in order to find the functions (the ELFs) that transform the at-sensor radiance L_u or digital counts into L_w or R_{rs} at the sea surface.

The ELF can fail at large off-nadir viewing directions (longer atmospheric paths), or if the atmospheric conditions vary over the scene.

Atmospheric Correction Techniques

Radiative transfer techniques such as TAFKAA can give good results for any atmospheric conditions, viewing geometry, and do not require extrapolation or zero water-leaving radiances. They are therefore widely used.

The disadvantage is that they require measurement, or modeling, or guessing, of the atmospheric properties needed to decide what correction to use at each pixel (for TAFKAA, the look-up table has >60,000,000 values to chose from!)

RT corrections will fail if you input inaccurate atmospheric properties (aerosol type and concentration, humidity, sea-level pressure, etc.). You never have all of the measurements needed for exact calculations (altitude profiles of aerosols, humidity, etc.)

Revised Requirements for Atmos Correction

We need to have an atmospheric correction technique that

- works for any water body (Case 1 or 2, deep or shallow)
- works for any atmosphere (including absorbing aerosols, which are common in coastal areas)
- does not require zero water-leaving radiance at particular wavelengths (no "black pixel" assumption)
- does not require ancillary field measurements that are expensive or difficult (or impossible) to obtain on a routine basis

No one has yet figured out a way to do atmospheric correction that meets these requirements. Fame awaits you!

"Curt, you're a hard man to please. You'll never be able to do atmospheric correction with the accuracy you require."

Spectrum Matching Techniques

When the atmos correction is good, then we can use spectrum-matching techniques to retrieve bathymetry, bottom reflectance, and water IOPs from calibrated $R_{rs}(\lambda)$.

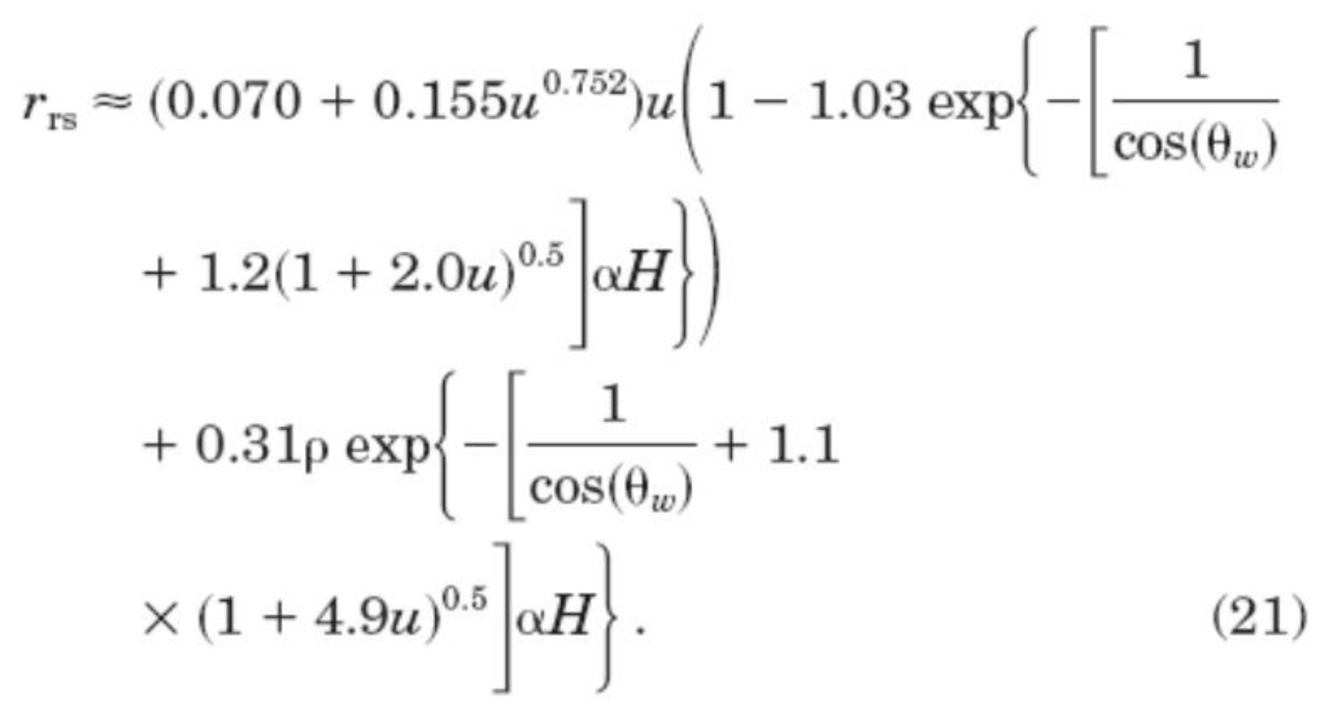
Match the image $R_{rs}(\lambda)$ spectra either to

- a semi-analytic model. The best-fit spectrum determines the model parameters (depth, IOPs, bottom refl) (Lee et al, *Appl Opt*, 1988, 1989; Dekker et al, *Limnol. Oceanogr. Methods*, 2011)

- a database of $R_{rs}(\lambda)$ spectra, for which the depth, bottom type, and IOPs are known for each database spectrum (Mobley et al., *Applied Optics*, 2005)

The Original Lee Semi-analytic Model

(Derivation and results are in the papers)



$$\begin{aligned} r_{\mathrm{rs}} \approx {} & (0.070 + 0.155u^{0.752})u\Bigg(1 - 1.03\exp\Bigg\{-\Bigg[\frac{1}{\cos(\theta_w)} \\ & + 1.2(1 + 2.0u)^{0.5}\Bigg]\alpha H\Bigg\}\Bigg) \\ & + 0.31\rho\exp\Bigg\{-\Bigg[\frac{1}{\cos(\theta_w)} + 1.1 \\ & \times (1 + 4.9u)^{0.5}\Bigg]\alpha H\Bigg\}. \end{aligned} \tag{21}$$

Unknown parameters: $u = b_b/(a + b_b)$; $\alpha = a + b_b$; ρ is the bottom reflectance, and H is the bottom depth. θ_w is the known in-water sun zenith angle.

Forcing this function to fit R_{rs} determines the unknowns

Spectrum Matching and Look-Up-Table R_{rs} Inversion

(Mobley et al., 2005. *Applied Optics*, 44(17), 3576-3592)

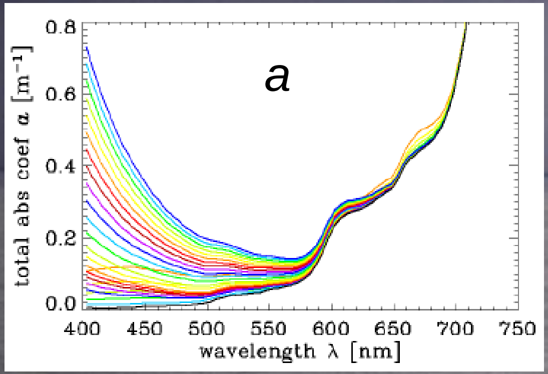
Rather than matching image $R_{rs}(\lambda)$ to a semi-analytical model, the spectra are matched to a database of R_{rs} spectra that correspond to known environmental conditions.

The first step is to create a database of R_{rs} spectra that correspond to all possible combinations of water absorption and scattering properties, bottom depths, and bottom reflectances that might be found in the area being studied. (Done with a special version of EcoLight; nadir-viewing R_{rs} only)

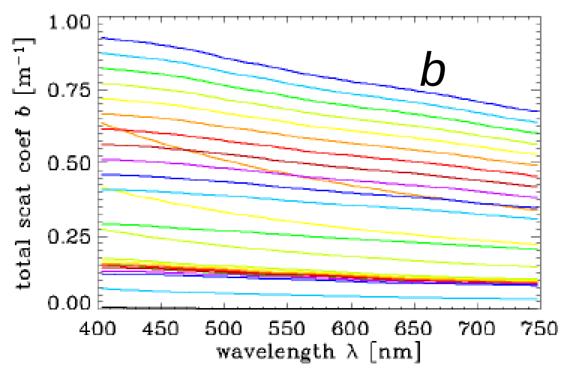
The database spectrum that is closest to the image spectrum then gives the retrieved environmental conditions.

CRISTAL METH: Comprehensive Reflectance Inversion based on Spectrum matching and TAble Lookup, Multi-Environment Techniques based on Hydrolight): proprietary software package developed by me to handle the creation of R_{rs} databases, image processing, and display of retrieved results.

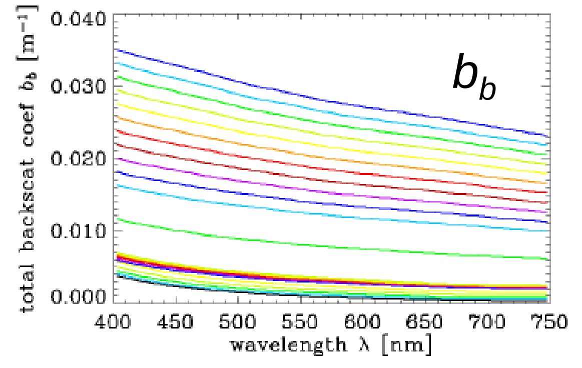
R_{rs} Database Creation



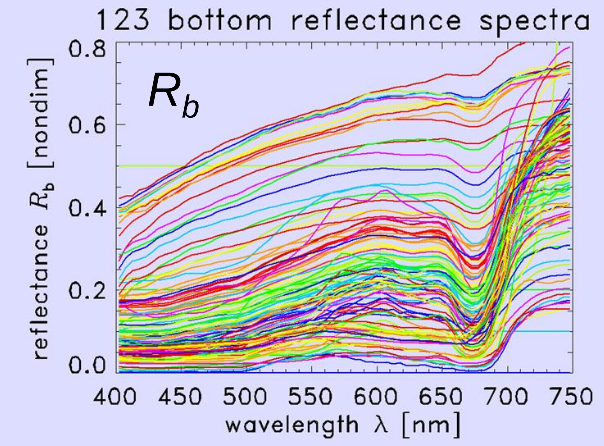
x



x



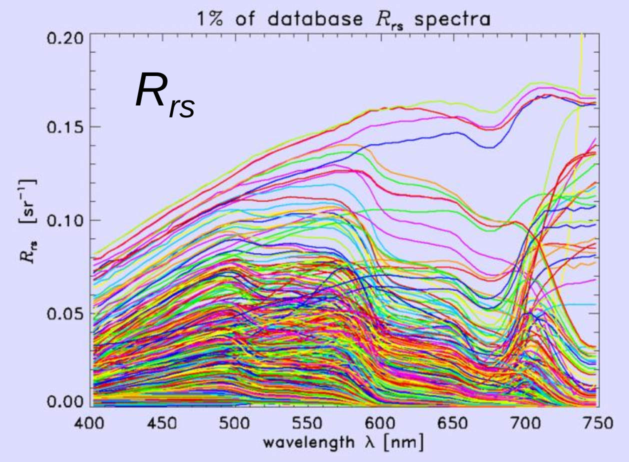
x



x

bottom depths
z_b = 0.01, 0.25, 0.75, 1.0,..., ∞

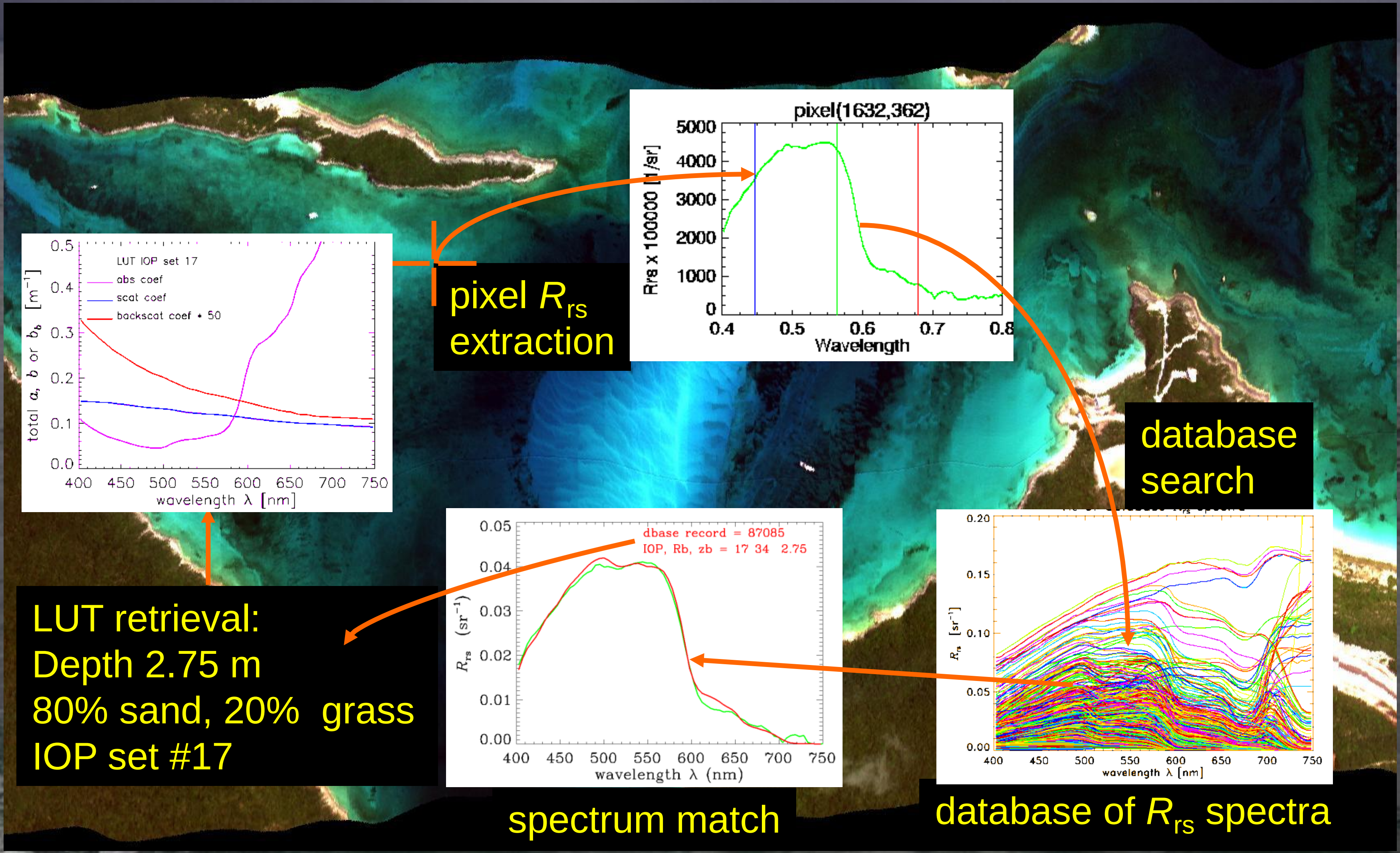
=



Many different absorption, scattering, backscatter, and bottom reflectance spectra, each for many different depths. These spectra can be based on observations or models. Each computed (using a special version of EcoLight) R_{rs} corresponds to known IOPs, depth, and bottom reflectance.

Image Processing

(after atmospheric correction)



pixel R_{rs} extraction

database search

LUT retrieval:
Depth 2.75 m
80% sand, 20% grass
IOP set #17

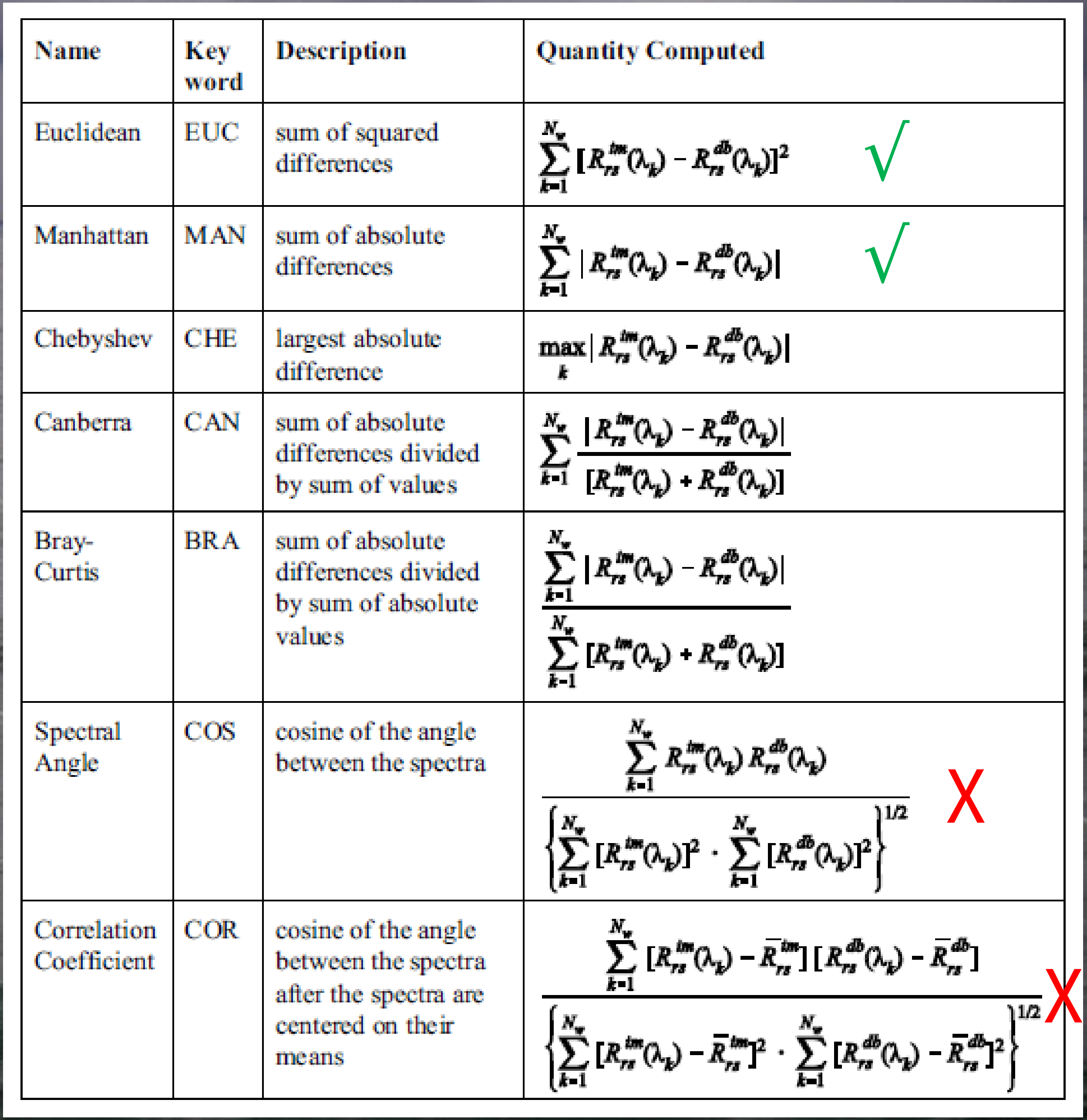
spectrum match

database of R_{rs} spectra

Metrics for Spectrum Matching

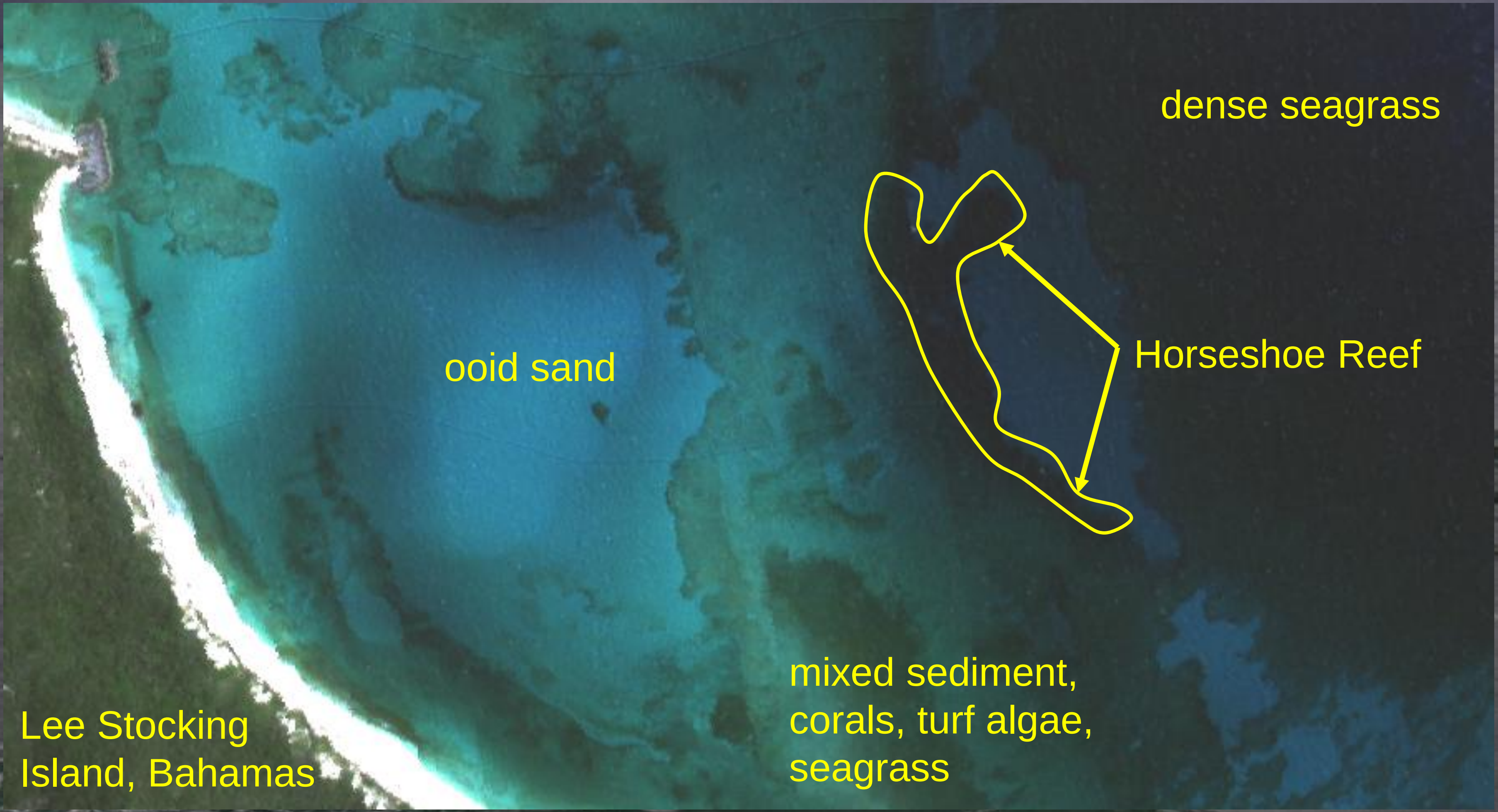
There is not a unique way to say how “close” one spectrum is to another.

Least-square and absolute value differences work best and run fastest.



Name	Key word	Description	Quantity Computed
Euclidean	EUC	sum of squared differences	$\sum_{k=1}^{N_w}[R_{rs}^{im}(\lambda_k)-R_{rs}^{db}(\lambda_k)]^2$ √
Manhattan	MAN	sum of absolute differences	$\sum_{k=1}^{N_w}\lvert R_{rs}^{im}(\lambda_k)-R_{rs}^{db}(\lambda_k)\rvert$ √
Chebyshev	CHE	largest absolute difference	$\max_k\lvert R_{rs}^{im}(\lambda_k)-R_{rs}^{db}(\lambda_k)\rvert$
Canberra	CAN	sum of absolute differences divided by sum of values	$\sum_{k=1}^{N_w}\frac{\lvert R_{rs}^{im}(\lambda_k)-R_{rs}^{db}(\lambda_k)\rvert}{[R_{rs}^{im}(\lambda_k)+R_{rs}^{db}(\lambda_k)]}$
Bray-Curtis	BRA	sum of absolute differences divided by sum of absolute values	$\frac{\sum_{k=1}^{N_w}\lvert R_{rs}^{im}(\lambda_k)-R_{rs}^{db}(\lambda_k)\rvert}{\sum_{k=1}^{N_w}[R_{rs}^{im}(\lambda_k)+R_{rs}^{db}(\lambda_k)]}$
Spectral Angle	COS	cosine of the angle between the spectra	$\frac{\sum_{k=1}^{N_w}R_{rs}^{im}(\lambda_k)\,R_{rs}^{db}(\lambda_k)}{\left\{\sum_{k=1}^{N_w}[R_{rs}^{im}(\lambda_k)]^2\cdot\sum_{k=1}^{N_w}[R_{rs}^{db}(\lambda_k)]^2\right\}^{1/2}}$ X
Correlation Coefficient	COR	cosine of the angle between the spectra after the spectra are centered on their means	$\frac{\sum_{k=1}^{N_w}[R_{rs}^{im}(\lambda_k)-\bar{R}_{rs}^{im}][R_{rs}^{db}(\lambda_k)-\bar{R}_{rs}^{db}]}{\left\{\sum_{k=1}^{N_w}[R_{rs}^{im}(\lambda_k)-\bar{R}_{rs}^{im}]^2\cdot\sum_{k=1}^{N_w}[R_{rs}^{db}(\lambda_k)-\bar{R}_{rs}^{db}]^2\right\}^{1/2}}$ X

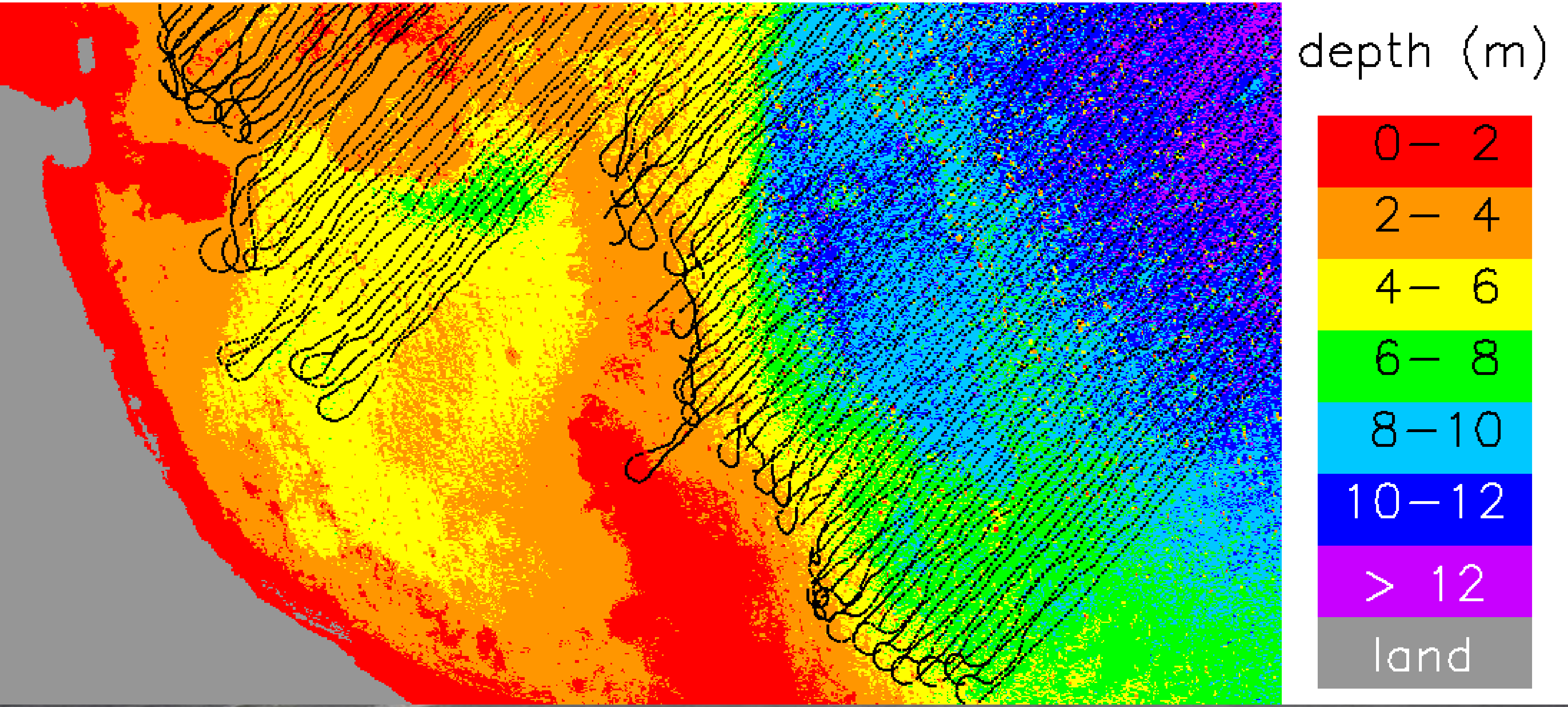
Example: Airborne Hyperspectral Image of Very Clear Water in the Bahamas



NRL-DC PHILLS image from ONR CoBOP program, May 2000

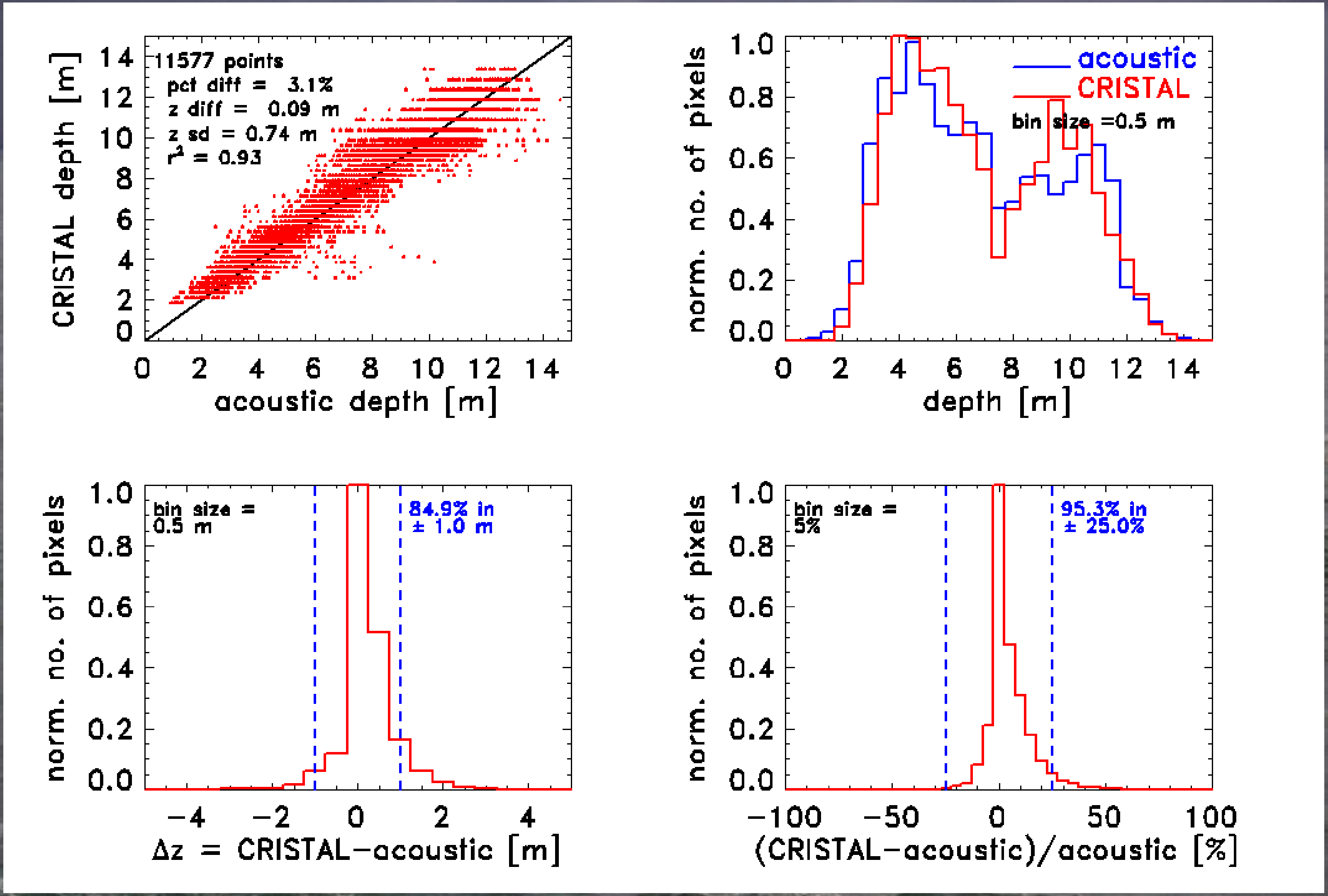
501x899 pixels at ~1.3 m resolution

Bathymetry Retrieval



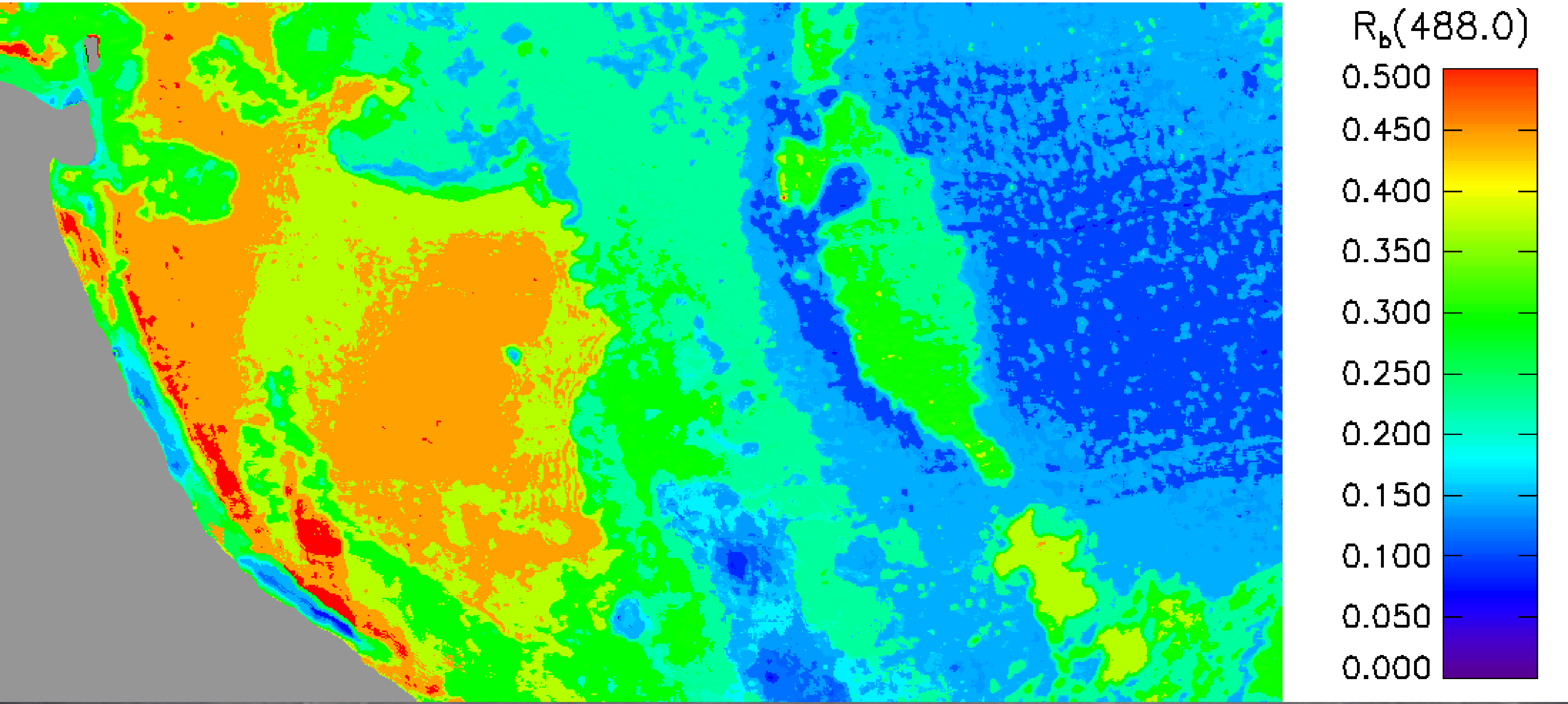
Black: NRL acoustic survey for ONR CoBOP program
Color: CRISTAL depth retrieval

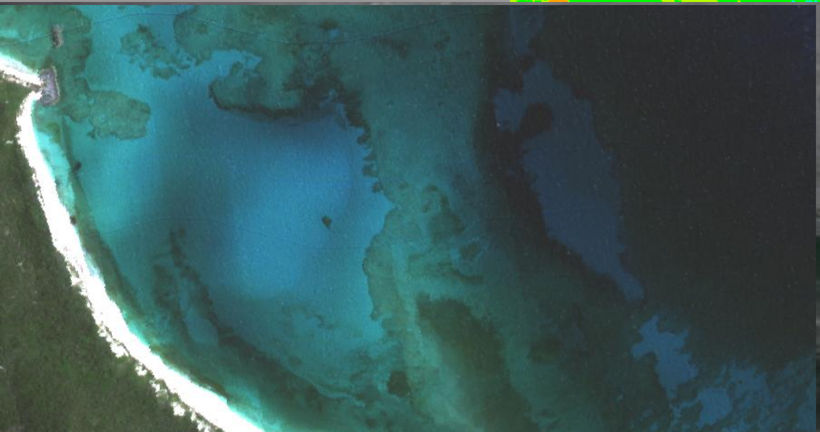
Depth Retrieval vs. Acoustic Bathymetry



These retrieval errors also include errors due to latitude-longitude calculations in mapping acoustic ping locations to image pixels (horizontal errors of several meters or more due to failure of built-in navigation instrument), and due to sun glint and whitecaps

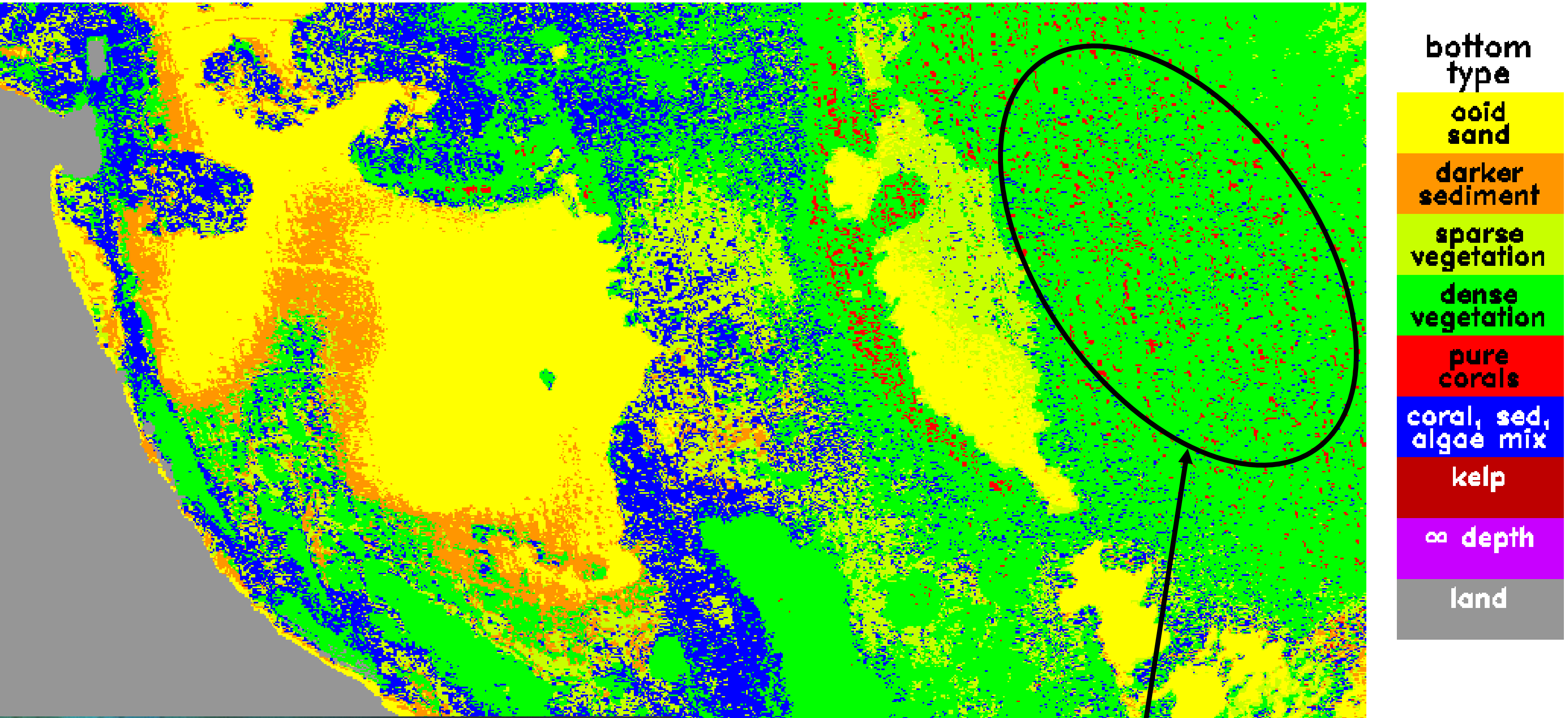
Bottom Reflectance

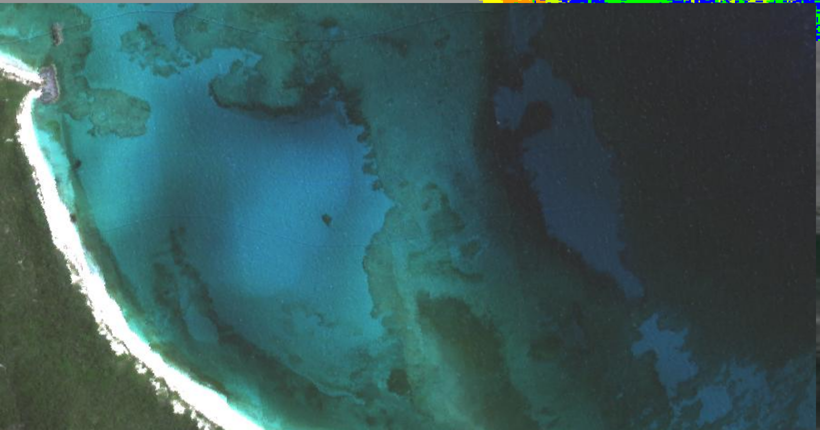


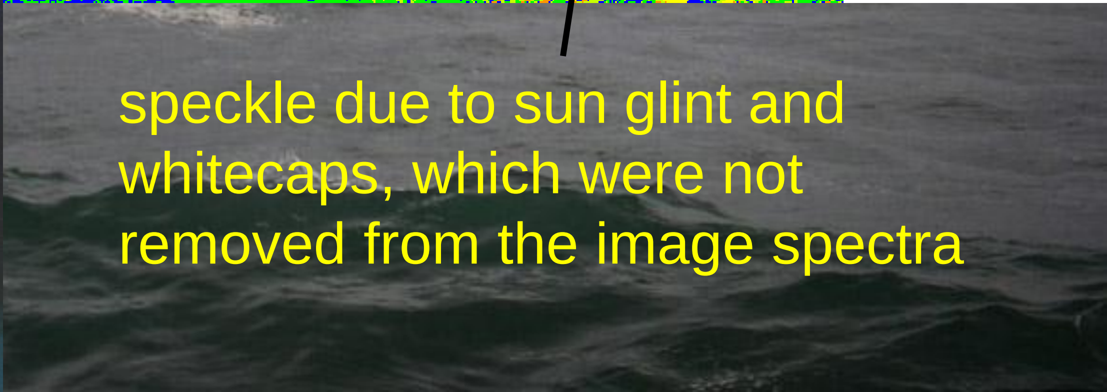


R_b(488) is what you would need for performance evaluation of a 488 nm bathymetric lidar

Bottom Classification





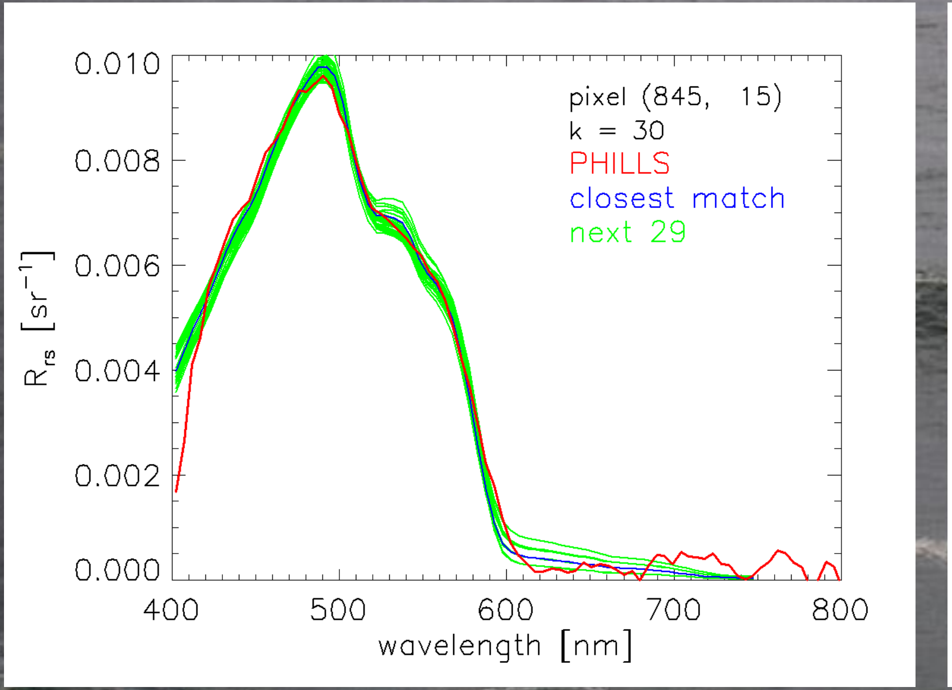


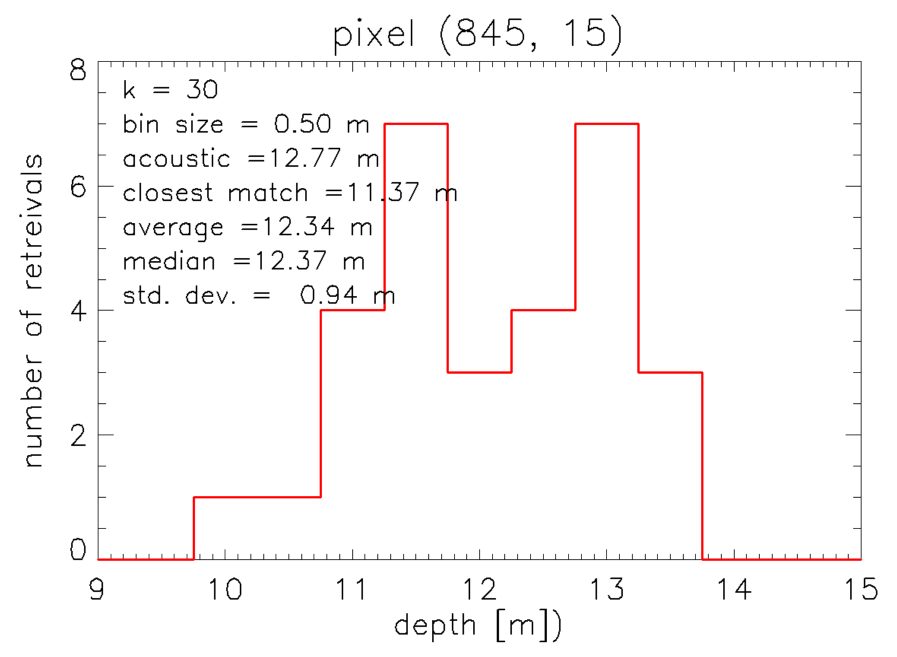
speckle due to sun glint and whitecaps, which were not removed from the image spectra

kNN Error Analysis

Being able to place error bars or confidence estimates on retrievals is often as important as the retrieved value itself

Can do this statistically from the distribution of retrieved values for the *k* closest matching spectra (k Nearest Neighbors, or kNN)

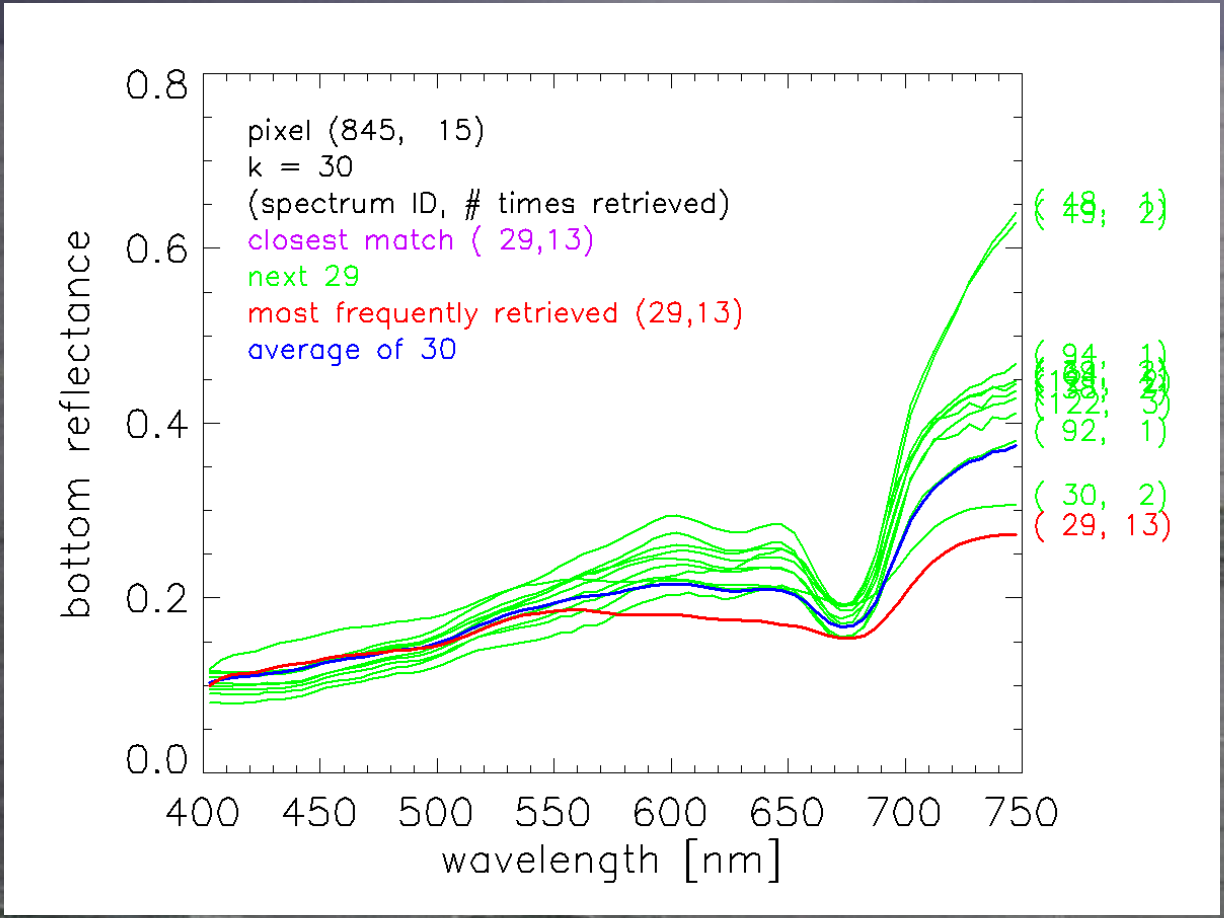




the 30 closest matches give a histogram of retrieved depths

the average or median gives a better estimate of the depth, plus an error estimate

kNN Error Analysis

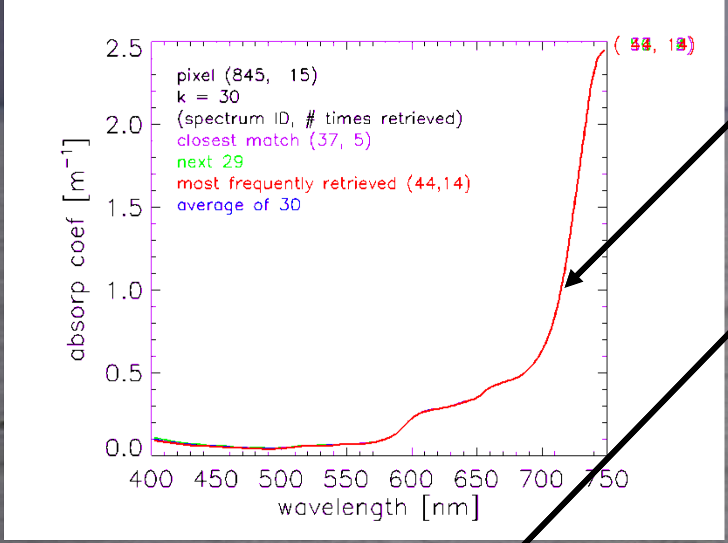


The closest and most frequently retrieved bottom reflectance spectrum was 30% sand and 70% seagrass.

The other bottoms are similar mixtures of sand and grass, sargassum, turf algae, and macrophytes.

So we can be fairly certain that the bottom is dense vegetation, probably sea grass

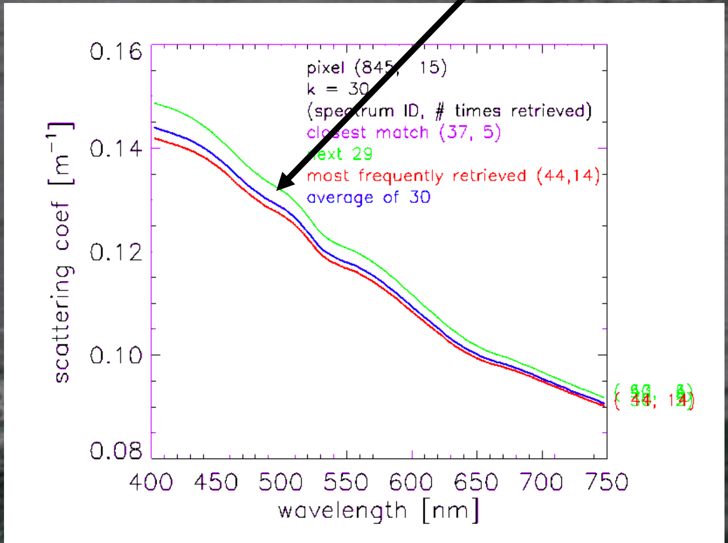
kNN Error Analysis

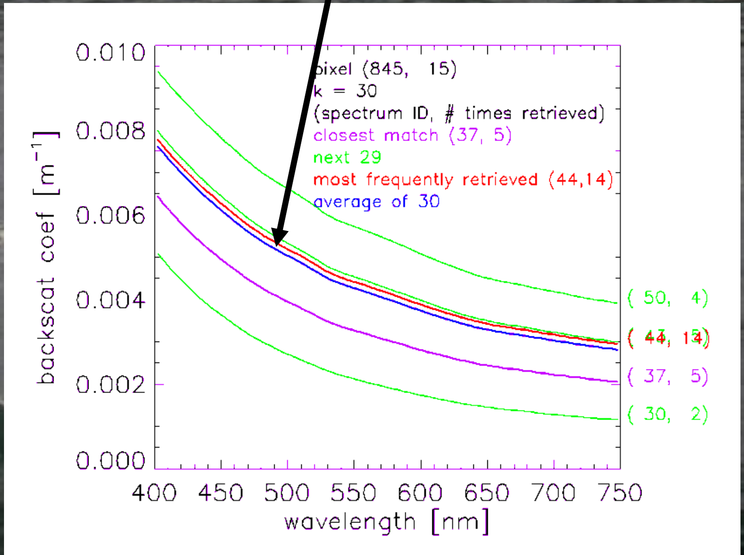


The retrieval is very certain about the absorption coefficient

The retrieval is fairly certain about the scattering coefficient

The retrieval is UNcertain about the backscatter coefficient



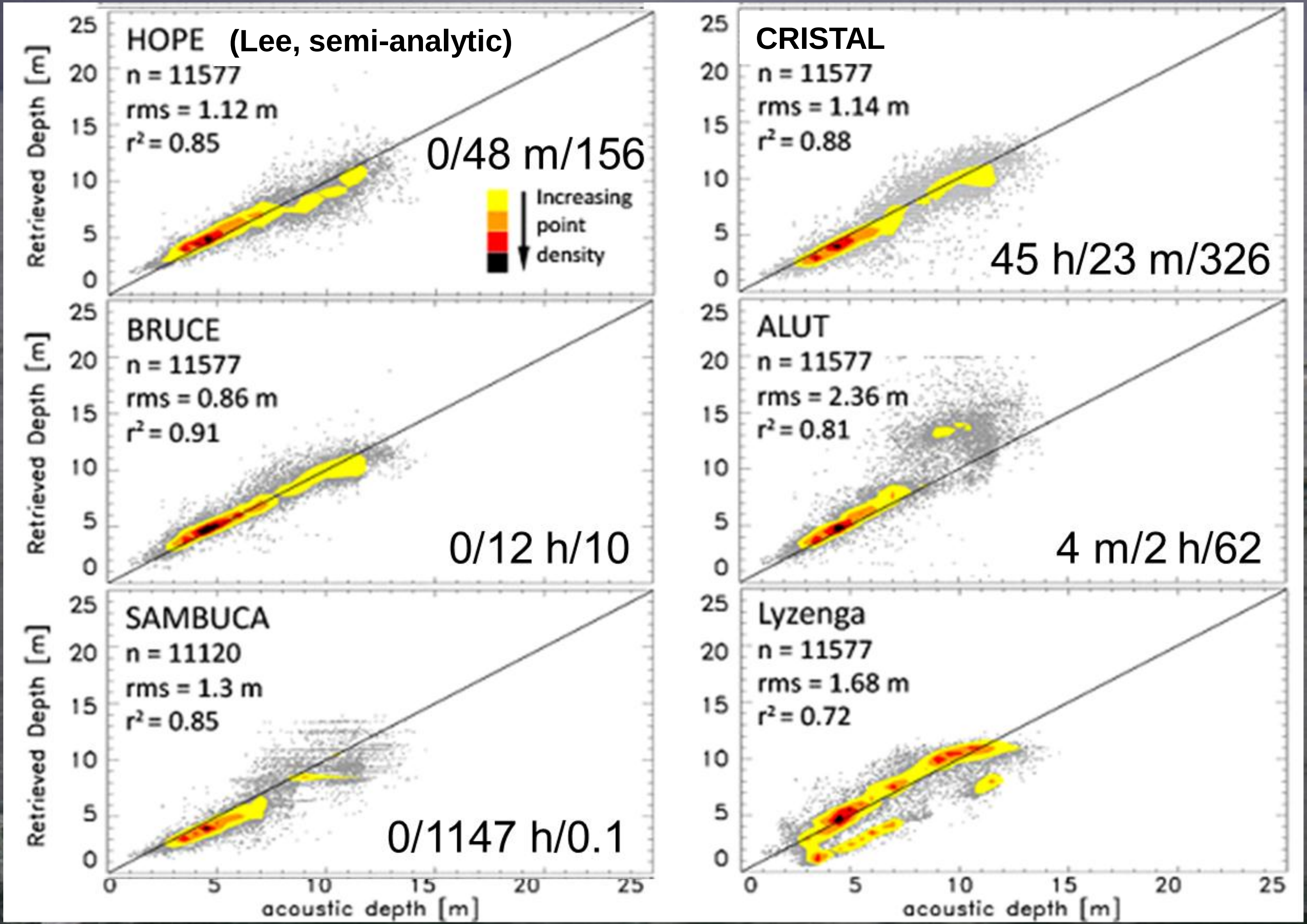


Does This Make Sense?

- In these very clear waters, the water absorption determines how much light gets to the bottom and back to the surface. Water-column scattering and backscatter contribute less to the water-leaving radiance in shallow water than does the bottom reflectance.
- The retrieval was therefore most certain about the absorption coefficient, and least certain about backscatter.
- The bottom reflectances all had similar reflectance spectra because it's the reflectance that is important. The retrieval wasn't able to distinguish between sea grass, turf algae, *sargassum*, and macrophytes, which all have similar reflectances.
- In very shallow (<5 m) clear water, the retrieved bottom reflectance becomes very certain and the water scattering and backscatter very uncertain (i.e., least important in determining R_{rs})

Comparison with other Algorithms

preprocessing time / image processing time / pixels per sec



From Dekker et al, 2012, *Limnol. Ocean. Methods*

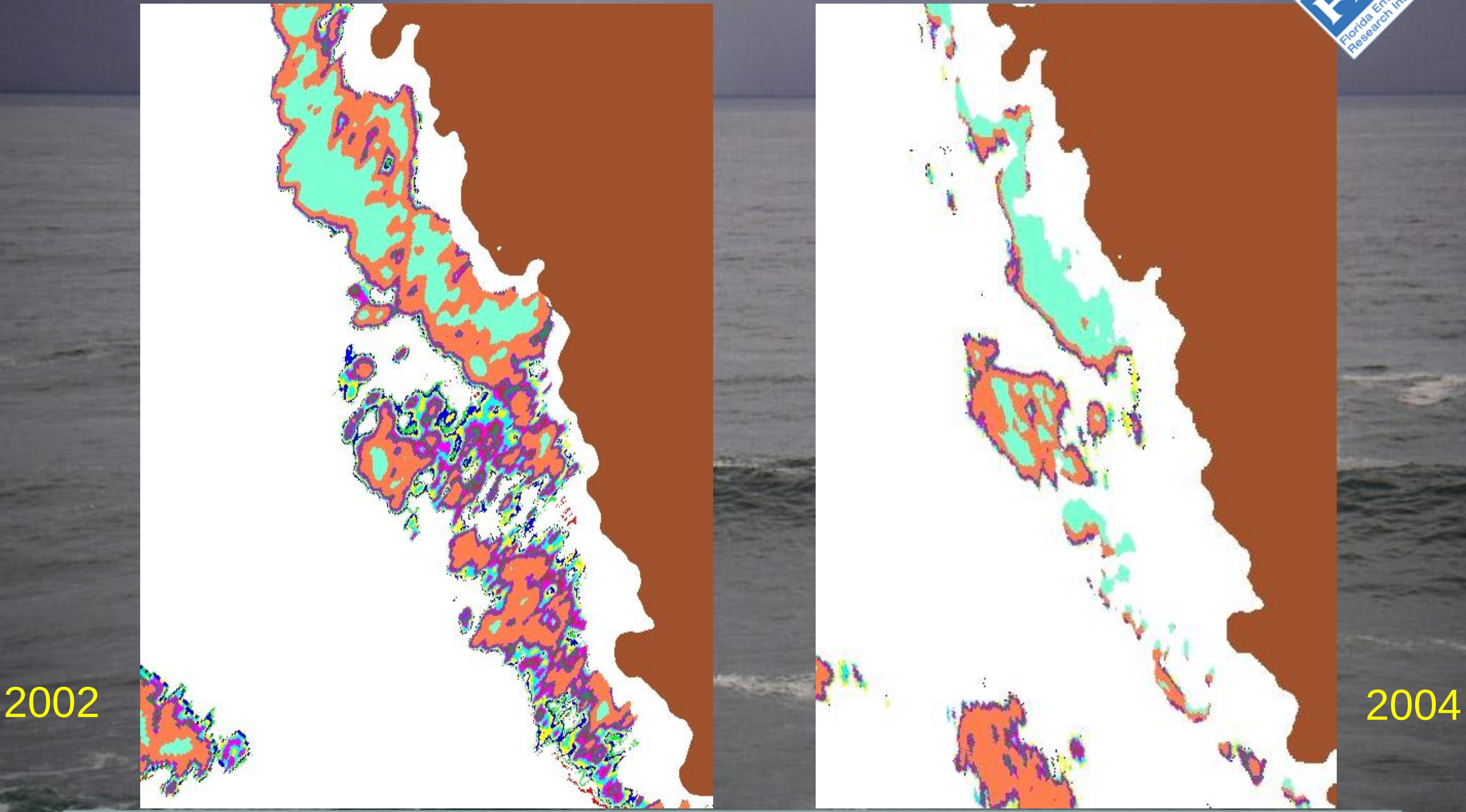
Kelp Mapping

Bull kelp (*Nereocystis luetkeana*) is very important for food, medicines, sheltering of fish, and recreational diving. Harvesting is strictly managed in the US.

http://www.bestpicturesof.com/misc/pictures%20of%20bull+kelp/?page=2#Google

http://www.beachwatchers.wsu.edu/ezidweb/seaweeds/Nereocystis.htm

Mapping of Kelp Coverage California Coast



DEM Land 0 % 10 % 20 % 30 % 40 % 50 %
60 % 70 % 80 % 90 % 100 % *100 %

Humboldt Bay California
Eel Grass Mapping

Chaeli Judd, MS Thesis, Judd et al., 2006

HSI determined eel grass distributions, previously unknown.

Species-level Mapping in Australian Waters

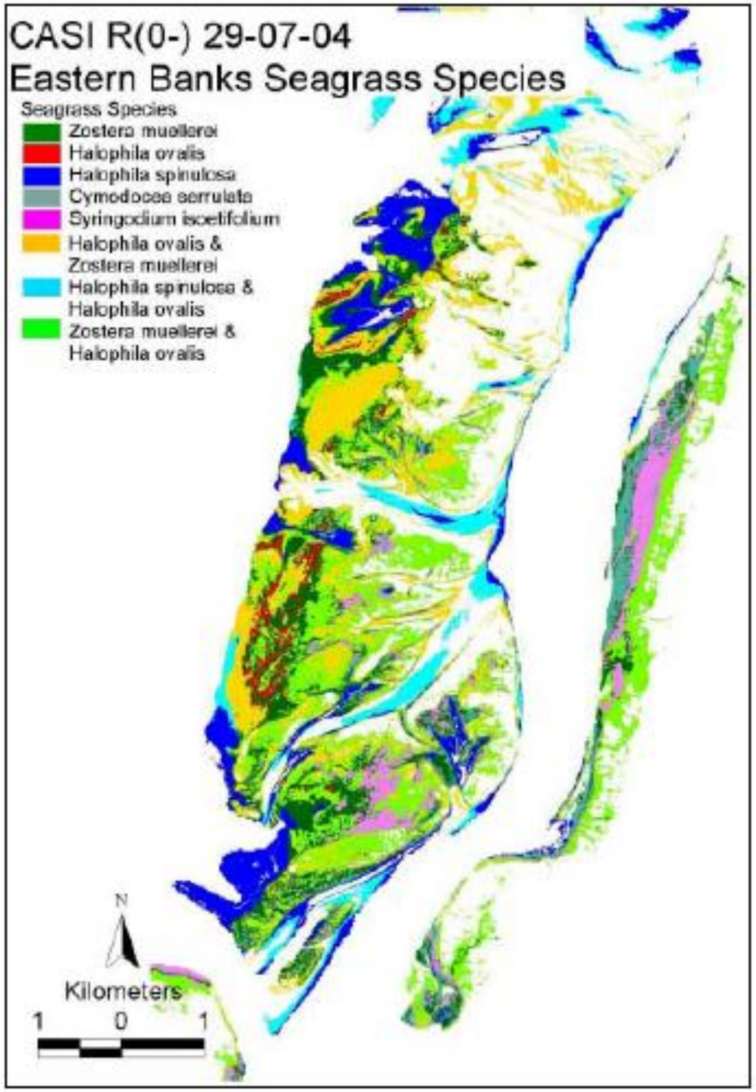


Figure 23a. Seagrass species composition maps to 3.0 m depth for the Eastern Banks, derived from Quickbird-2 image

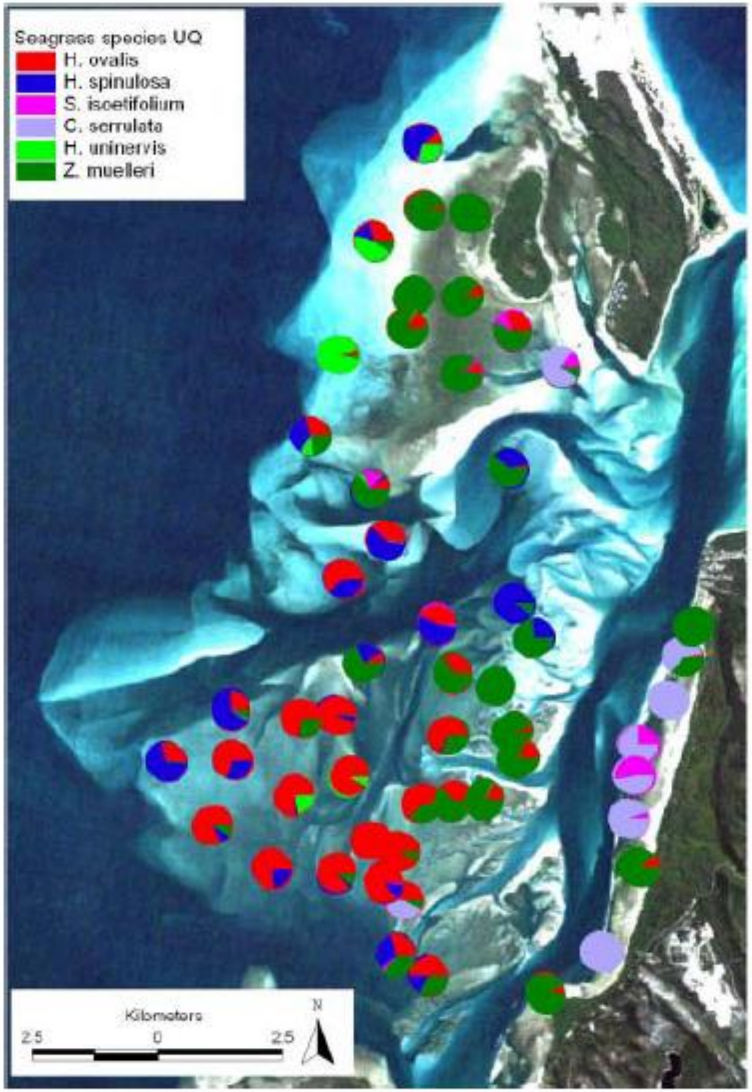
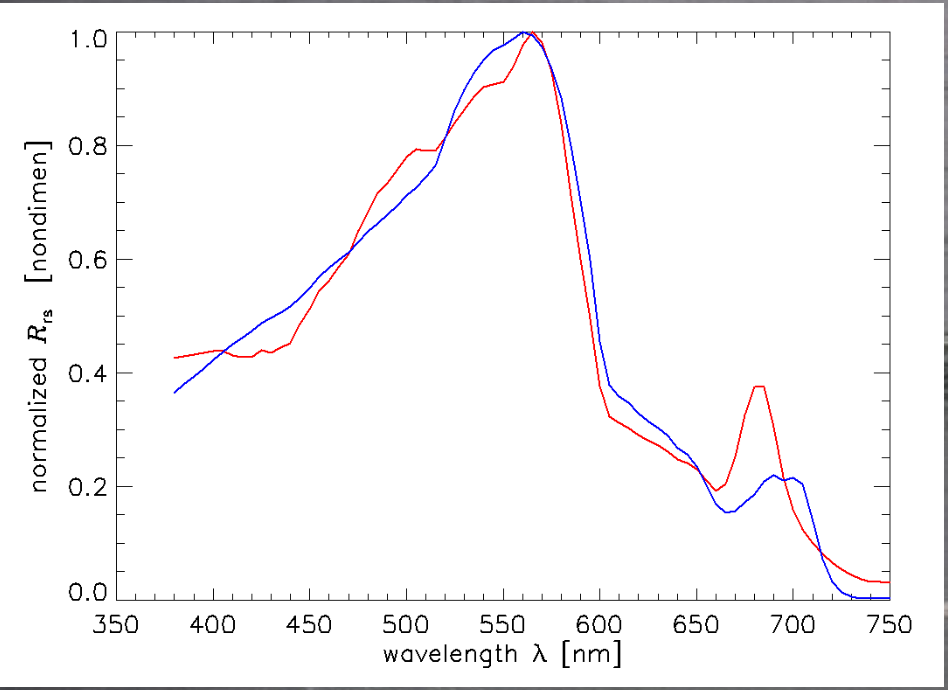


Figure 16. Transect-level summaries for field survey of seagrass species composition, collected from Eastern Banks in July 2004

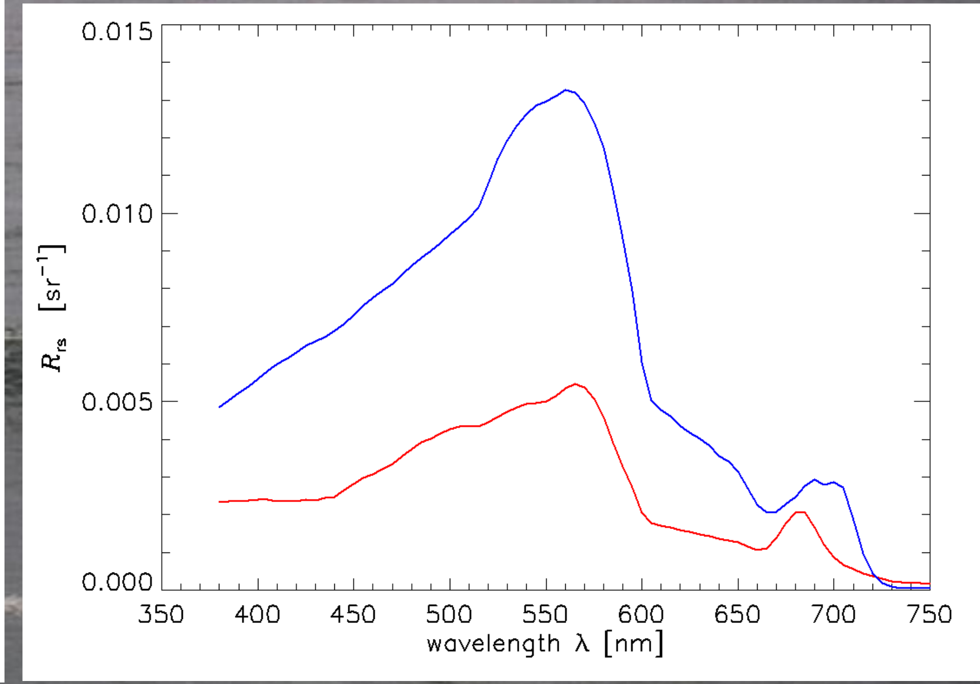
Phinn, et al., 2006

Uniqueness: Not a Problem (yet?)

Having well calibrated R_{rs} spectra removes the non-uniqueness that plagues band-ratio and other techniques that depend only on spectral shape. Both spectral shape and magnitude are critical.



normalized R_{rs} spectra

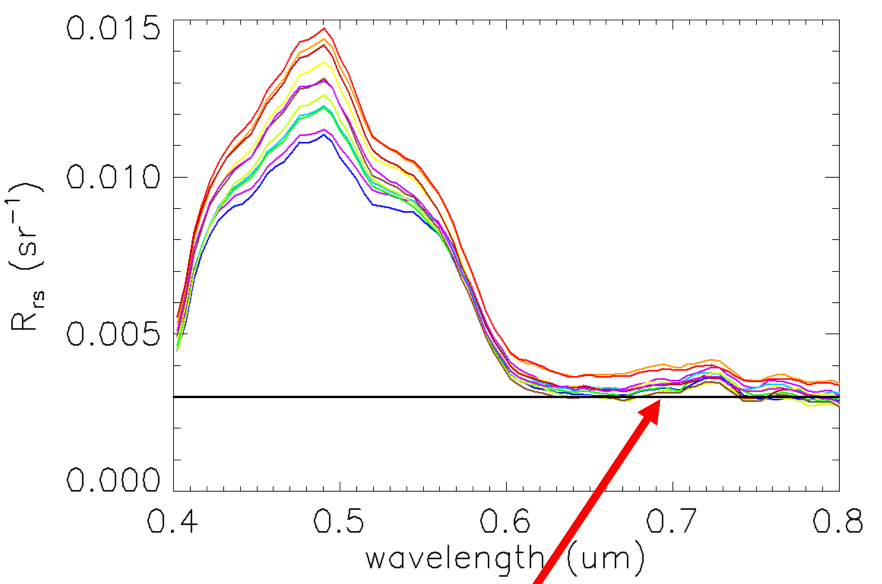


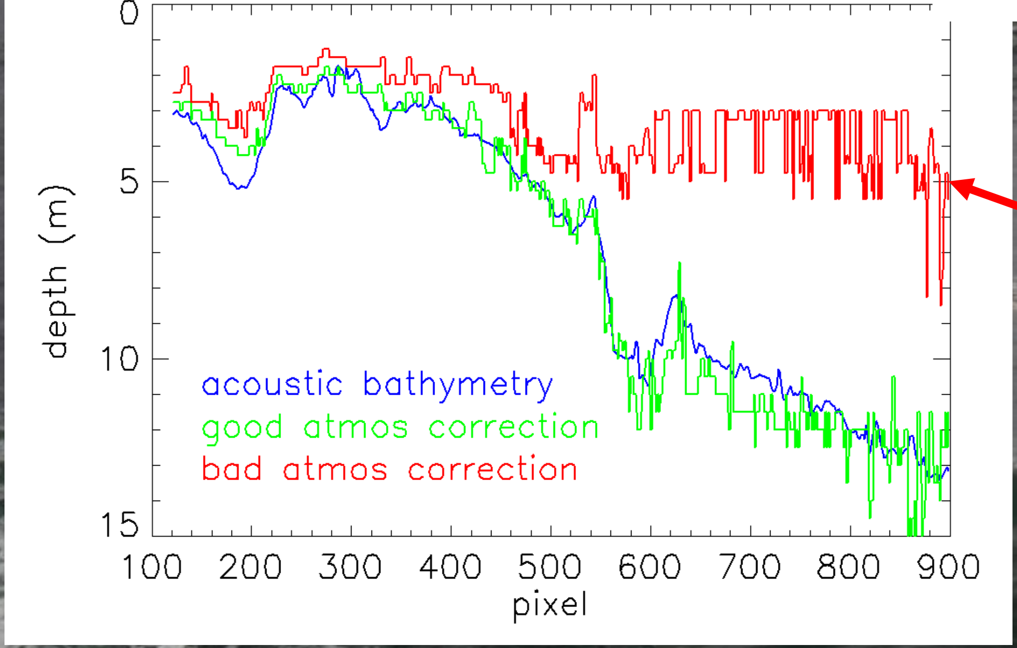
calibrated R_{rs} spectra

Red: infinitely deep water, Chl = 10 mg m^{-3}
Blue: 2 m deep clear water, sea grass bottom

Remaining Problems: Atmospheric Correction

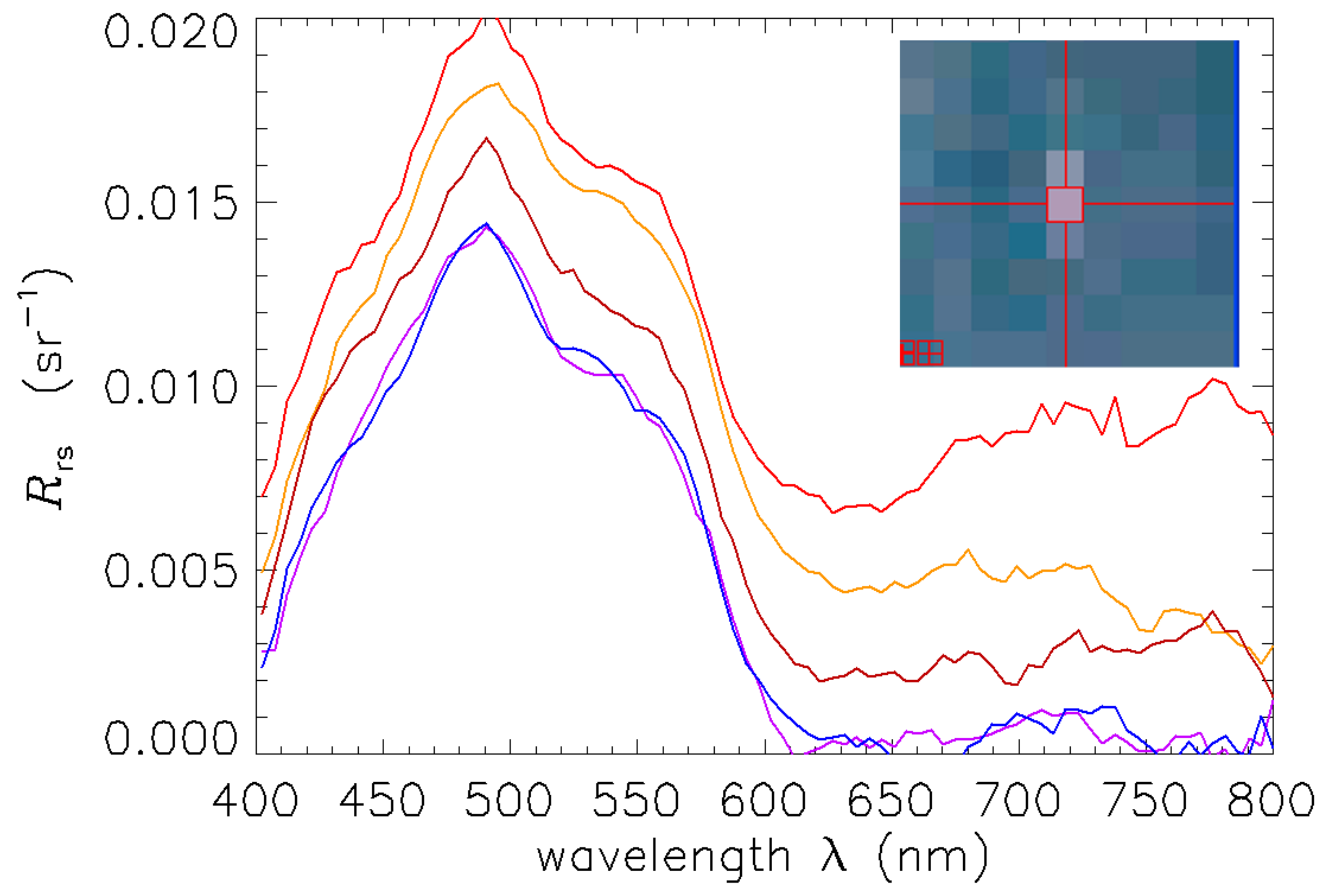
As always, good retrievals depend on having a good atmospheric correction





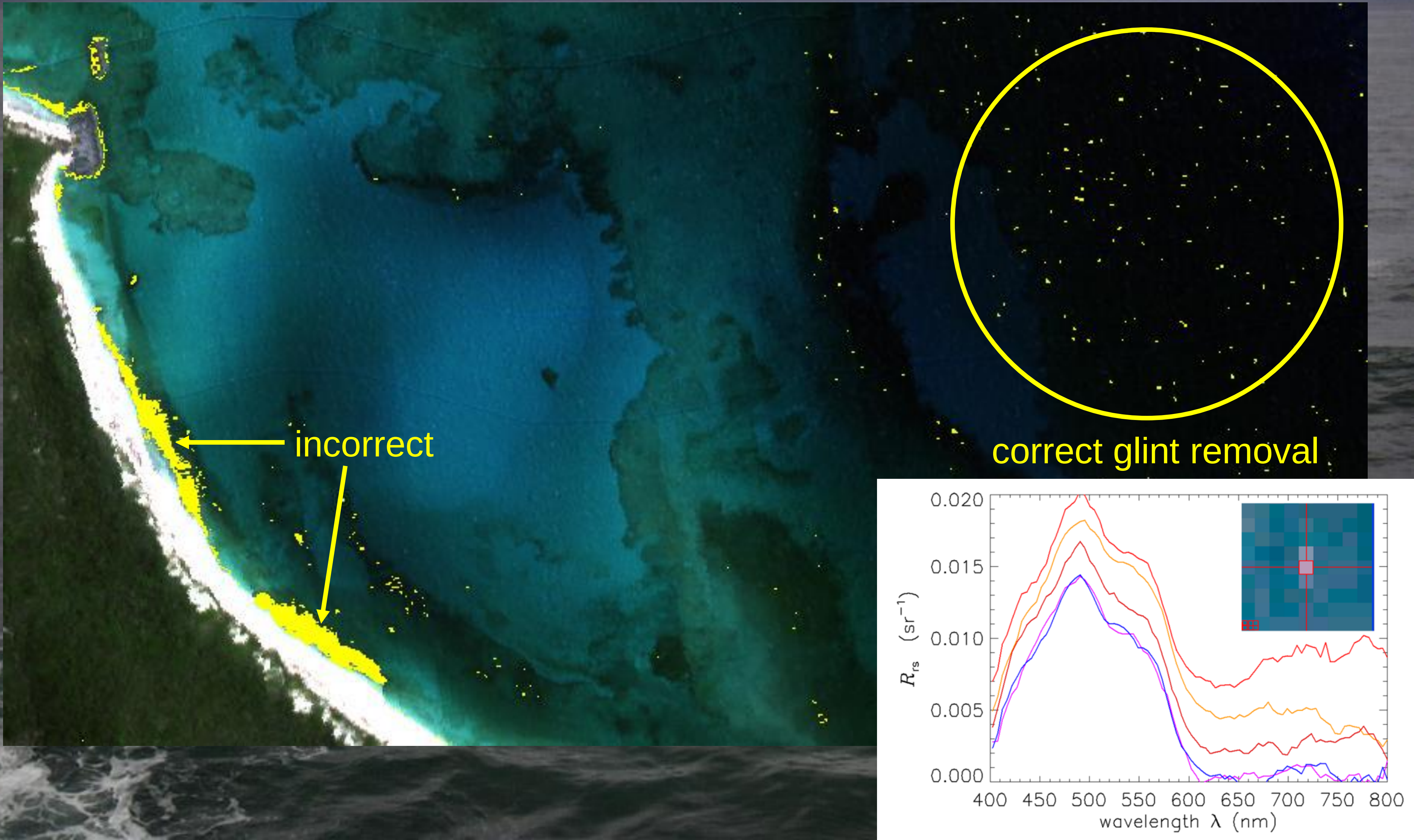
atmospheric undercorrection by 0.003 1/sr gives bottom depths too shallow

Remaining Problems: Glint Removal



Remaining Problems: Glint Removal

Standard algorithms for whitecap and glint removal also remove very shallow water (same for thin clouds)



Summary

Both database and semi-analytical spectrum-matching techniques for retrieval of bathymetry and bottom type have proven themselves and are now widely used.

However, all spectrum-matching techniques MUST have atmospherically well-corrected imagery. Bad atmos correction → bad retrievals.

Atmospheric correction for optically shallow or Case 2 waters, and for absorbing aerosols, requires ancillary measurements at the time of image acquisition, which are not possible on a routine basis. The unsolved problem of atmospheric correction is the limiting factor for remote sensing of coastal waters.

People I’ve Met Around the World

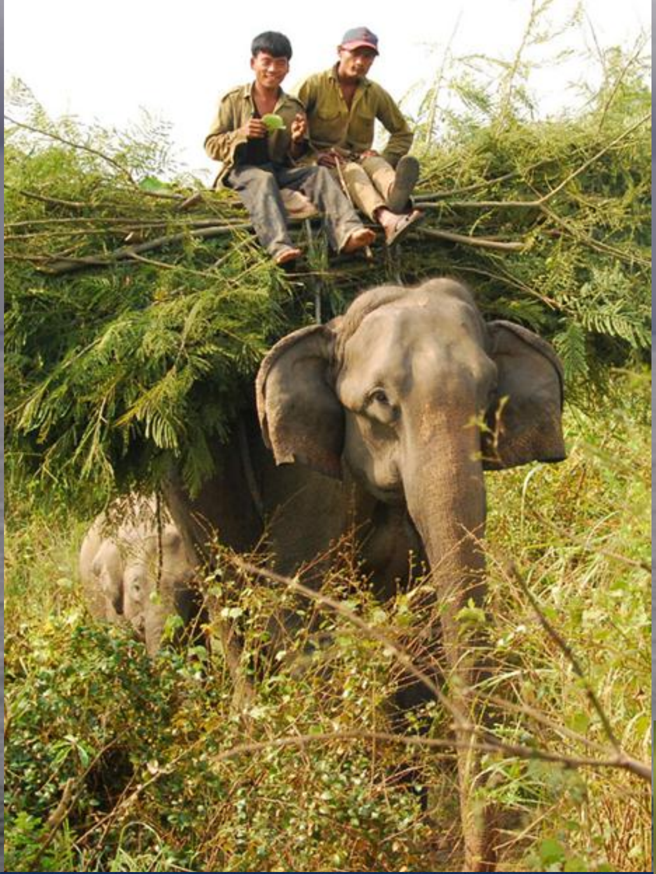
East Greenland, 2005

Panama, 2012

Yunnan, China, 2009

“The Other China” 2005-12

Nepal (2011)


The End!