The Unsolved Problem of Atmospheric Correction for Airborne Hyperspectral Remote Sensing of Shallow Waters

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Overview

This lecture:

- What's the problem and who cares
- Basic definitions
- Atmospheric Correction for Shallow Waters
  - Why "black pixel" techniques for deep, case 1 water don't work
  - Empirical Line Fit
  - Radiative Transfer

Next lecture:

- Spectrum-matching Techniques for Retrieval of Environmental Information (after the atmospheric correction has been done)

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 (sometimes to species level) 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 are needed at 1-10 meter spatial scales (not kilometers), and sometimes on-demand with results within ~1 day of image acquisition. Hyperspectral is needed for species discrimination.

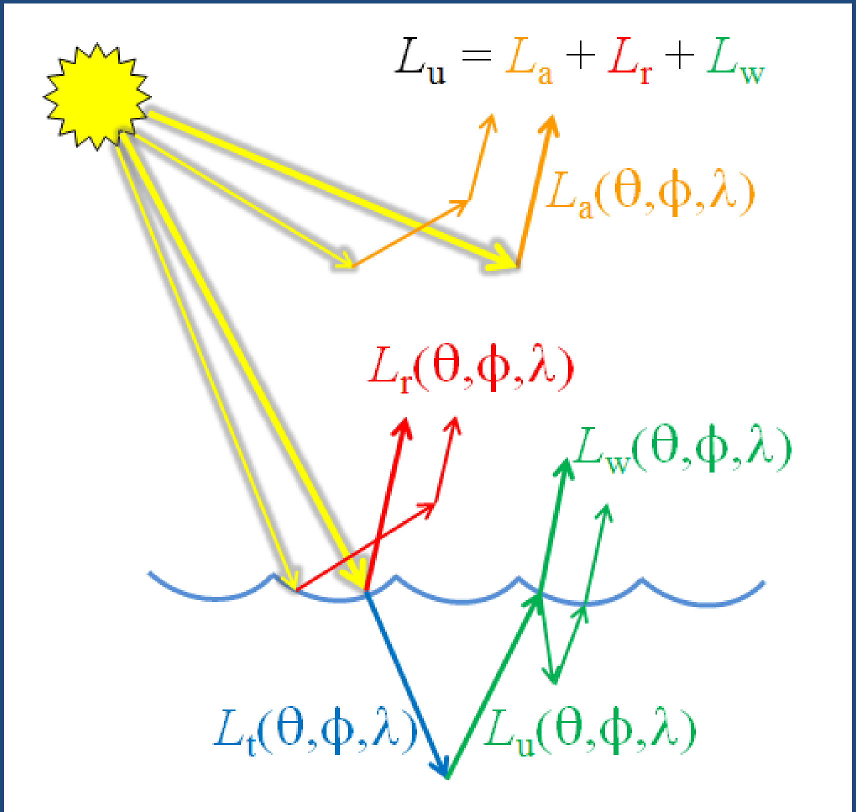
Counting Photons

You can't get meter-scale hyperspectral imagery from a polar-orbiting satellite because there just aren't enough photons reaching the TOA. See www.oceanopticsbook.info/view/remote_sensing/level_2/counting_photons for order-of-magnitude estimates.

- View a larger surface area, which both increases the number of photons leaving the surface and allows for longer integration times.
- View the surface area for a longer time, e.g., from a geostationary satellite that can stare at the same point for very long times (but a geostationary satellite has an altitude of 36,000 km, which makes the solid angle much smaller).
- Increase the bandwidth.
- Increase the aperture of the receiving optics.
- Use multiple detector elements to observe the same ground pixel nearly simultaneously, either on the same or successive scans, and then combine the photons collected from the different sensors
- Get closer to the surface, e.g. by using an airborne sensor flying at a few kilometers above the sea surface. This greatly increases the solid angle of the sensor and allows for longer integration times for a slowly flying aircraft.

The praticable solution: Fly low and slow with an airborne hyperspectral sensor

At-sensor Radiance and Atmospheric Correction



L_a is the atmospheric path radiance (scattering from molecules and aerosols)

L_r is surface-reflected radiance (sun and sky glint or glitter)

L_w is the water-leaving radiance

Each of these terms is signal to someone, and noise to someone else

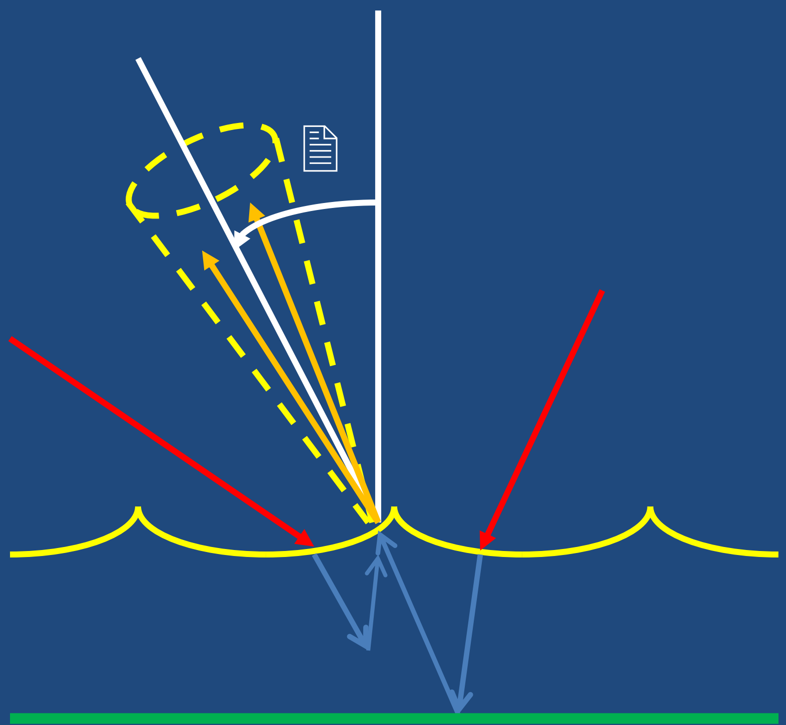
A sensor measures the sum, L_u

Atmospheric correction (or atmospheric compensation) is the process of extracting L_w from a measurement of L_u

Remote-sensing Reflectance R_{rs}

$$R_{rs}(\theta,\varphi,\lambda) = \frac{\text{upwelling water-leaving radiance}}{\text{downwelling plane irradiance}}$$

$$R_{rs}(\text{in air},\theta,\varphi,\lambda) \equiv \frac{L_w(\text{in air},\theta,\varphi,\lambda)}{E_d(\text{in air},\lambda)} \qquad [\text{sr}^{-1}]$$



sea surface

bottom

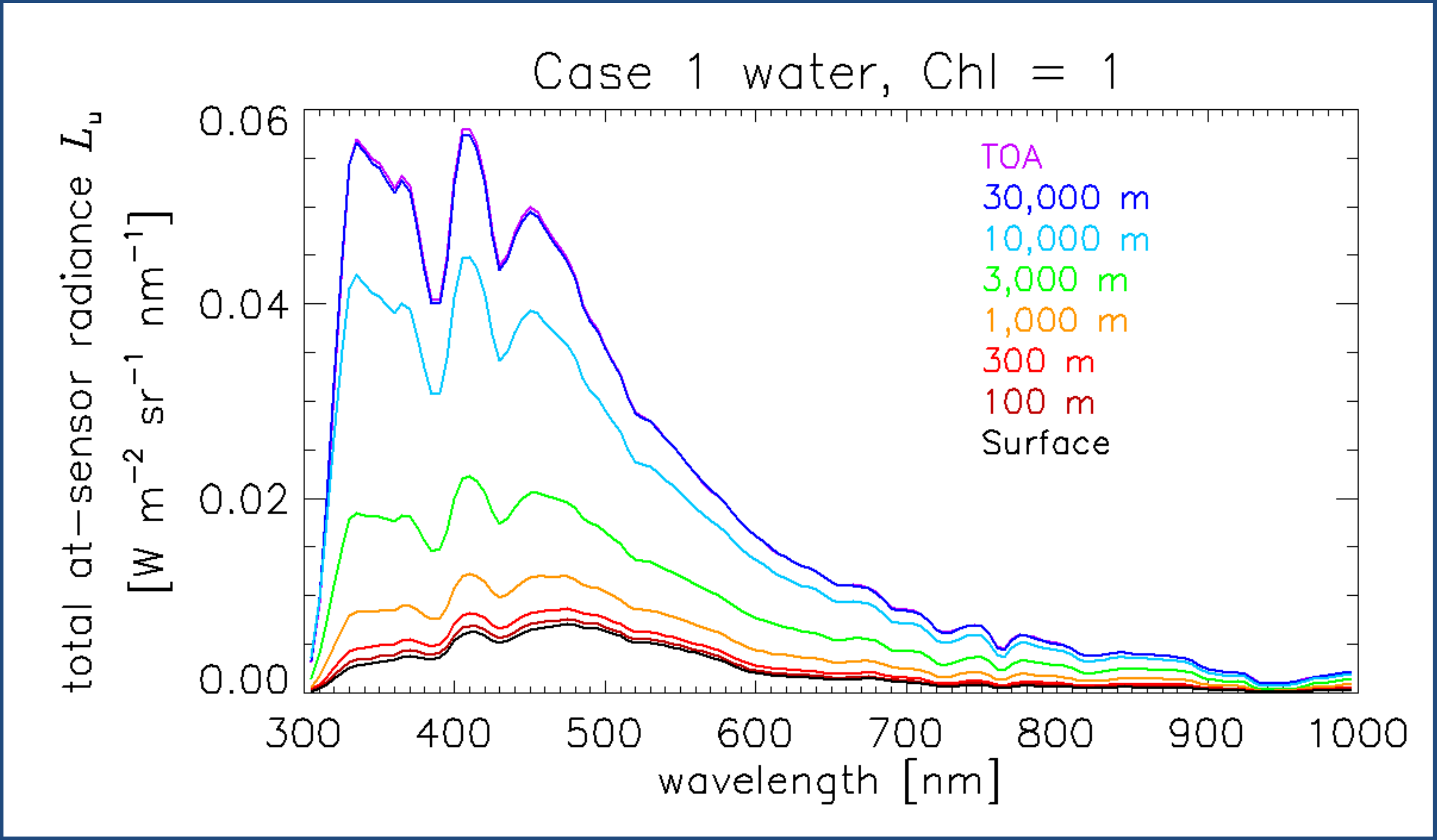
The fundamental quantity used today in ocean color remote sensing

Often use the nadir-viewing R_{rs}, i.e. the radiance that is heading straight up from the sea surface (θ = 0)

Equivalent non-dimensional reflectance: $\rho = \pi R_{rs}$

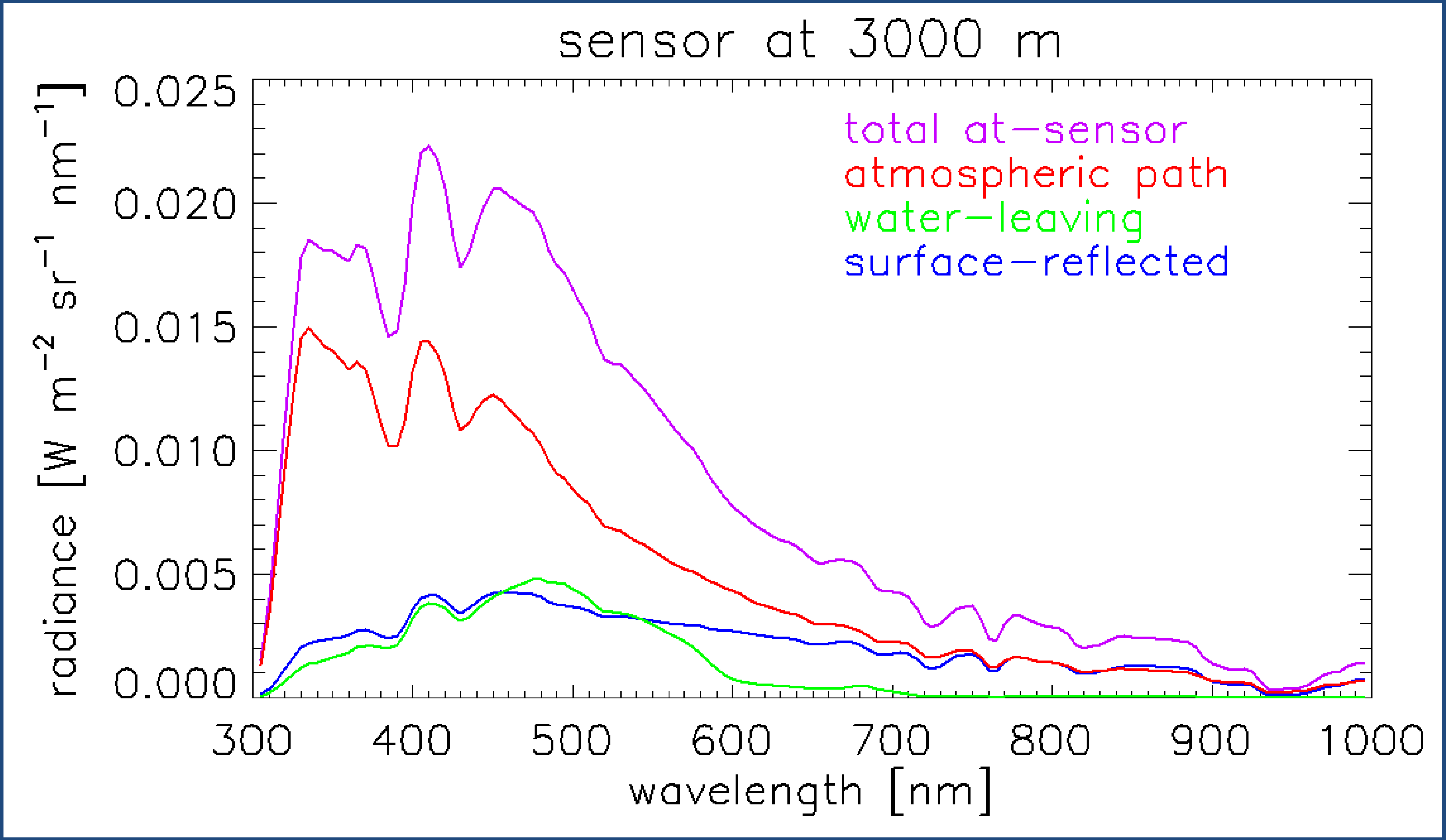
Atmospheric Contributions to L_u

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



HydroLight-Modtran simulations

All Contributions to L_u



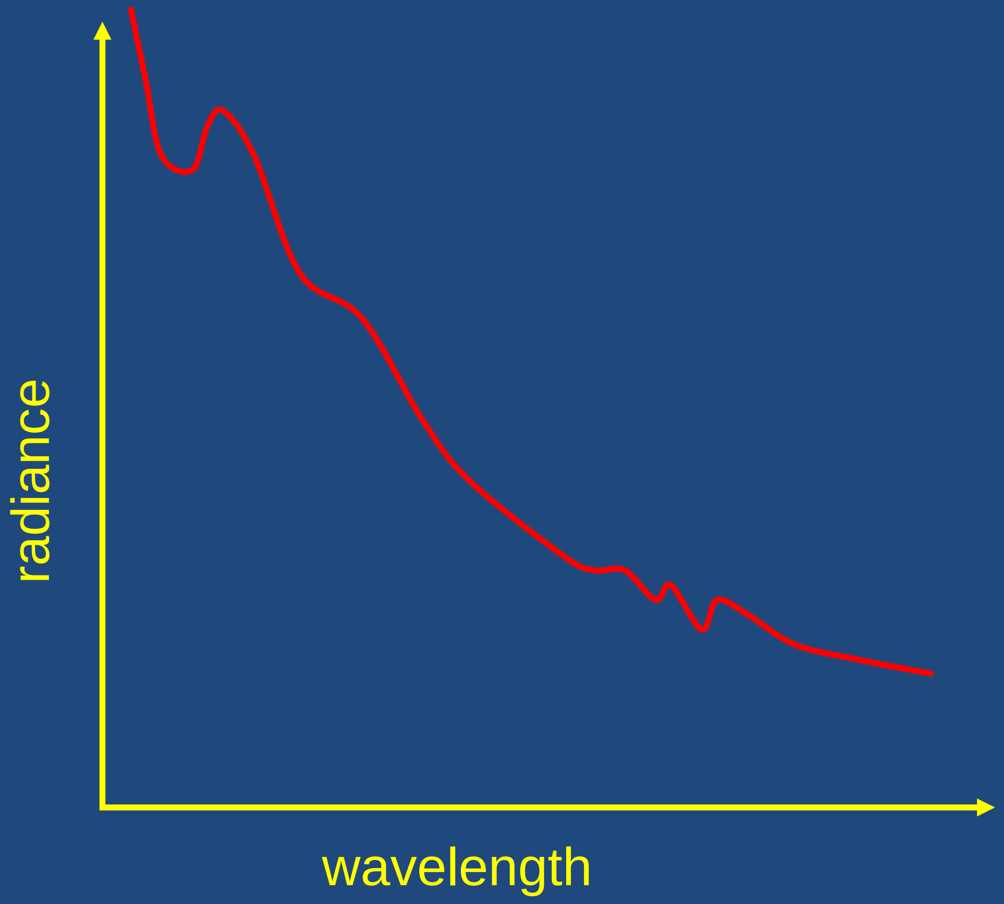
Three Techniques for Atmospheric Correction

- "Black-pixel" technique: developed for open-ocean (usually Case 1 water), multi-spectral, satellite ocean color remote sensing (SeaWiFS, MODIS, etc.) Many papers by Howard Gordon and others; Menghua Wang will cover in detail. Works well for deep Case 1 water, but fails for optically shallow and highly scattering Case 2 waters.

- Empirical Line Fit (ELF): A correlational technique that relates measured sea-level R_{rs} spectra to at-sensor radiances. In principle can correct for any atmospheric conditions, but requires field measurements of R_{rs} at time of image acquisition

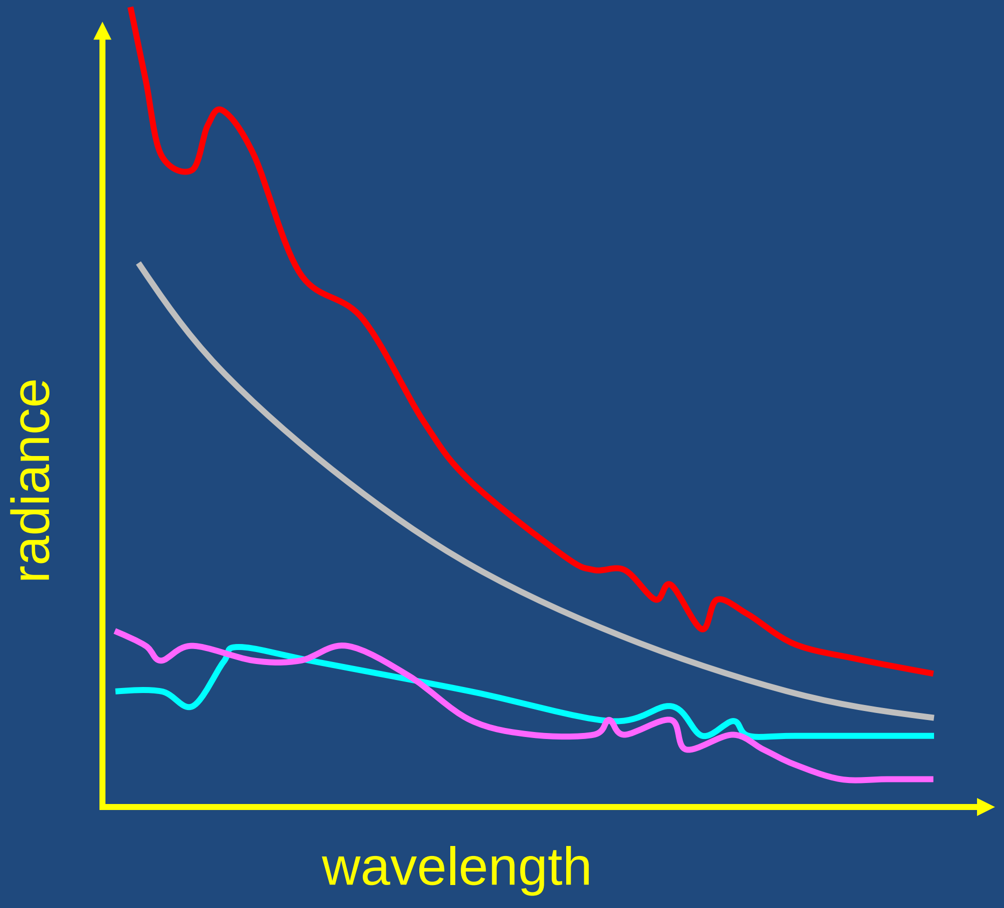
- Radiative Transfer Techniques: Explicitly compute and remove the atmospheric path radiance for given atmospheric conditions and viewing geometry. In principle can correct for any atmospheric conditions, but requires knowledge of atmospheric conditions at time of image acquisition

Black-pixel Technique and Extrapolation



measured at-sensor radiance

Black-pixel Technique and Extrapolation



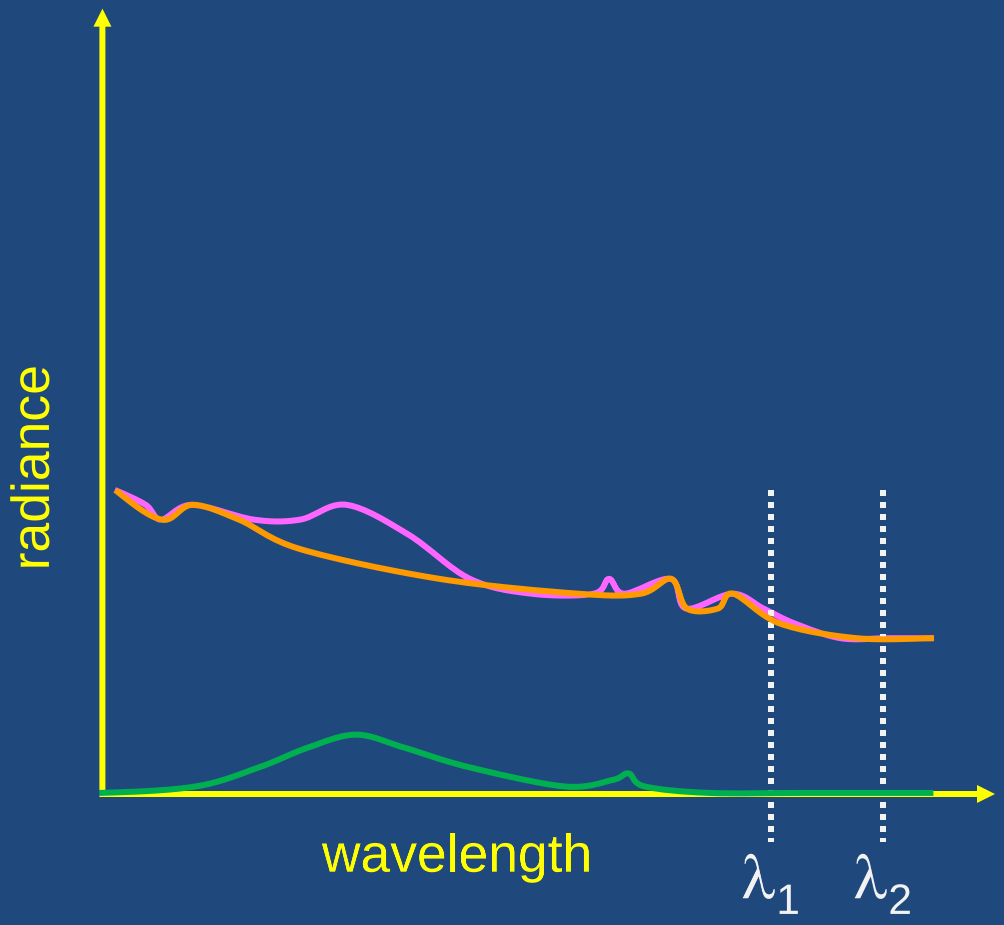
measured at-sensor radiance

compute the Rayleigh contribution

compute the surface-reflected contribution (sun and sky glint)

subtract to get the aerosol + water-leaving radiance

Black-pixel Technique and Extrapolation



aerosol + water-leaving radiance

Find an aerosol model that gives a good fit for $L(\lambda_1)$ and $L(\lambda_2)$ at 2 NIR wavelengths where L_w is zero. Use it to compute $L(\lambda)$ at all wavelengths (i.e., extrapolate from λ_1 and λ_2 to all wavelengths) and subtract

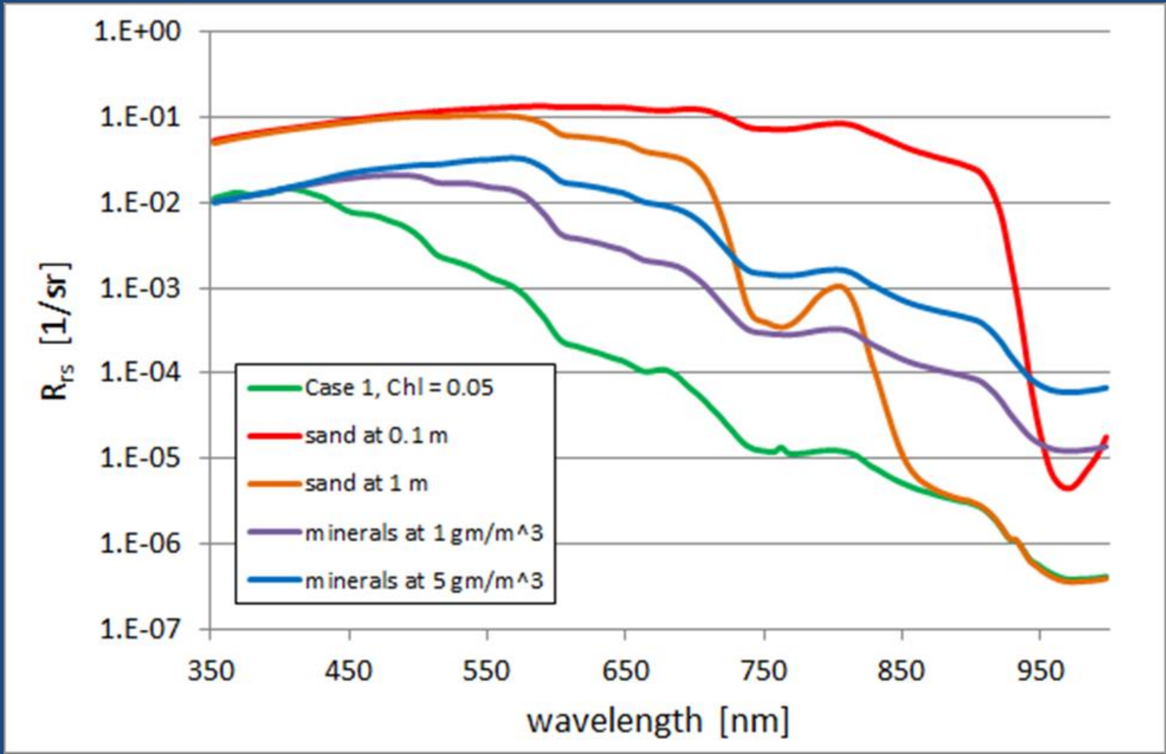
This leaves the water-leaving radiance L_w (i.e., R_{rs})

Black-pixel Technique and Extrapolation

This technique works well in many situations, but…

This technique DOES NOT WORK for remote-sensing of shallow waters, because bottom reflectance often makes $L_w(\lambda_1)$ and $L_w(\lambda_2)$ non-zero. It fails for Case 2 waters with high mineral concentrations, because scattering by mineral particles can also make $L_w(\lambda_1)$ and $L_w(\lambda_2)$ non-zero. It also fails if the aerosols are highly absorbing (dust, soot) as is often case in coastal waters.

It has inherent problems because small errors in the near IR can give big errors (even negative L_w) near 400 nm.



Requirements for Shallow or Case 2 Water

We need to have an atmospheric correction technique that

- does not require zero water-leaving radiance at particular wavelengths (no “black pixel” assumption)

- 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 ancillary field measurements that cannot be obtained on a routine basis or in denied-access areas

Faster, cheaper, better: pick any 2. Here it’s pick any 3.

Empirical Line Fit

- Measure R_{rs} at several points *within the image area at the time of image acquisition*

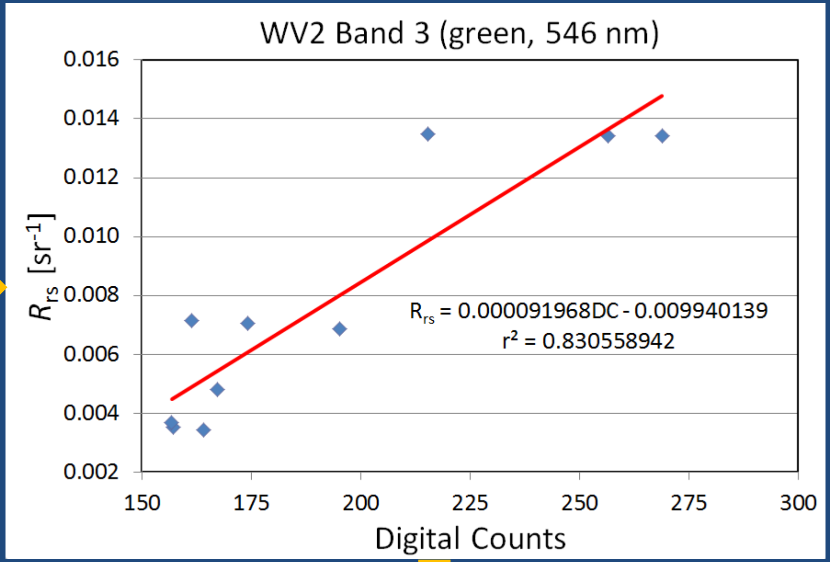
- Correlate the measured R_{rs} with the at-sensor signal at each wavelength to get a function—the empirical line fit—that converts at-sensor values to sea-level R_{rs}

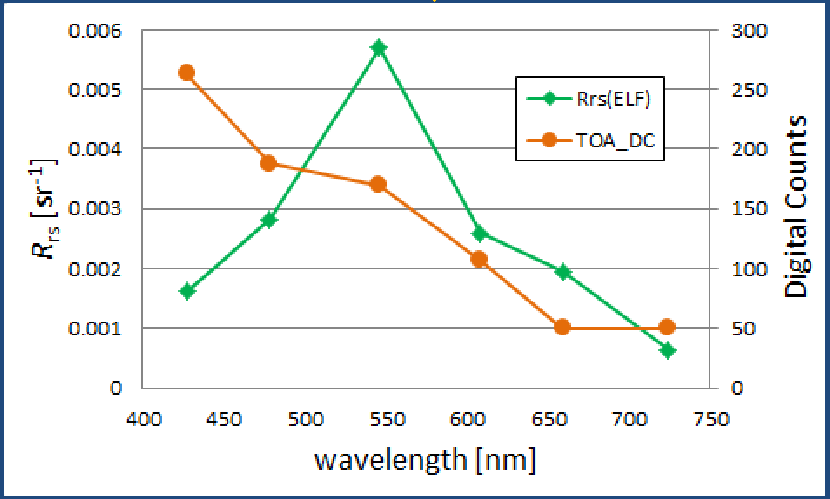
- Apply this ELF to all pixels in the image

- In principle, the ELF technique can correct for any atmospheric conditions (which do not need to be known)

Empirical Line Fit

Example using WorldView-2 satellite multispectral imagery of St. Joseph's Bay, FL





There is a different ELF for each wavelength

Empirical Line Fit

The major drawback of the ELF technique is that it requires someone in the field, usually in a small boat, to make the needed sea-surface R_{rs} measurements at the time of the overflight.

An ELF based on measurements in one part of the image will give a bad correction for an image if the atmospheric conditions vary over the image (clouds, variable aerosol concentration), or the sea surface reflectance varies (wind speed varies)

The ELF can also become inaccurate for large off-nadir viewing angles because of different atmospheric path lengths and scattering angles.

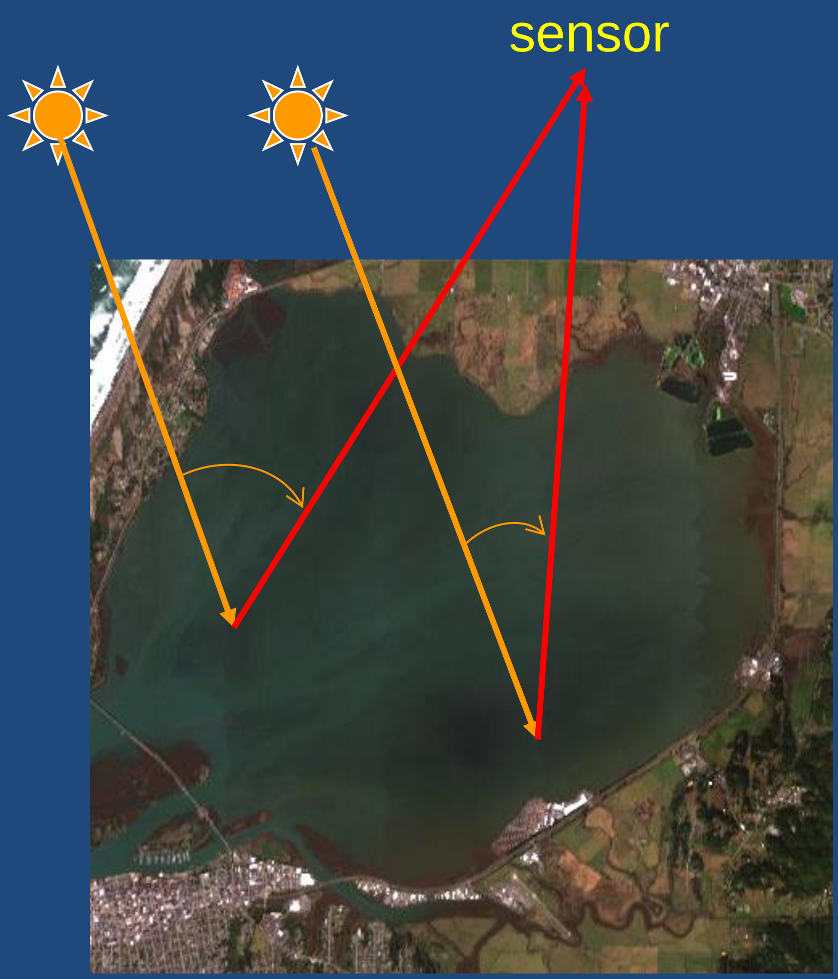
Radiative Transfer Techniques

If we know (or can estimate) the absorbing and scattering properties of the atmosphere, then we can use an atmospheric radiative transfer (RT) model to compute the atmospheric path radiance (and surface reflectance) 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 (Gao et al, 2000; Montes et al, 2001; 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 (aerosol type and concentration, surface pressure, humidity, etc). These calculations (including polarization) required ~6 x 10^7 RT simulations with TAFKAA, taking several months of time on a 256 processor SGI supercomputer.

Radiative Transfer Techniques

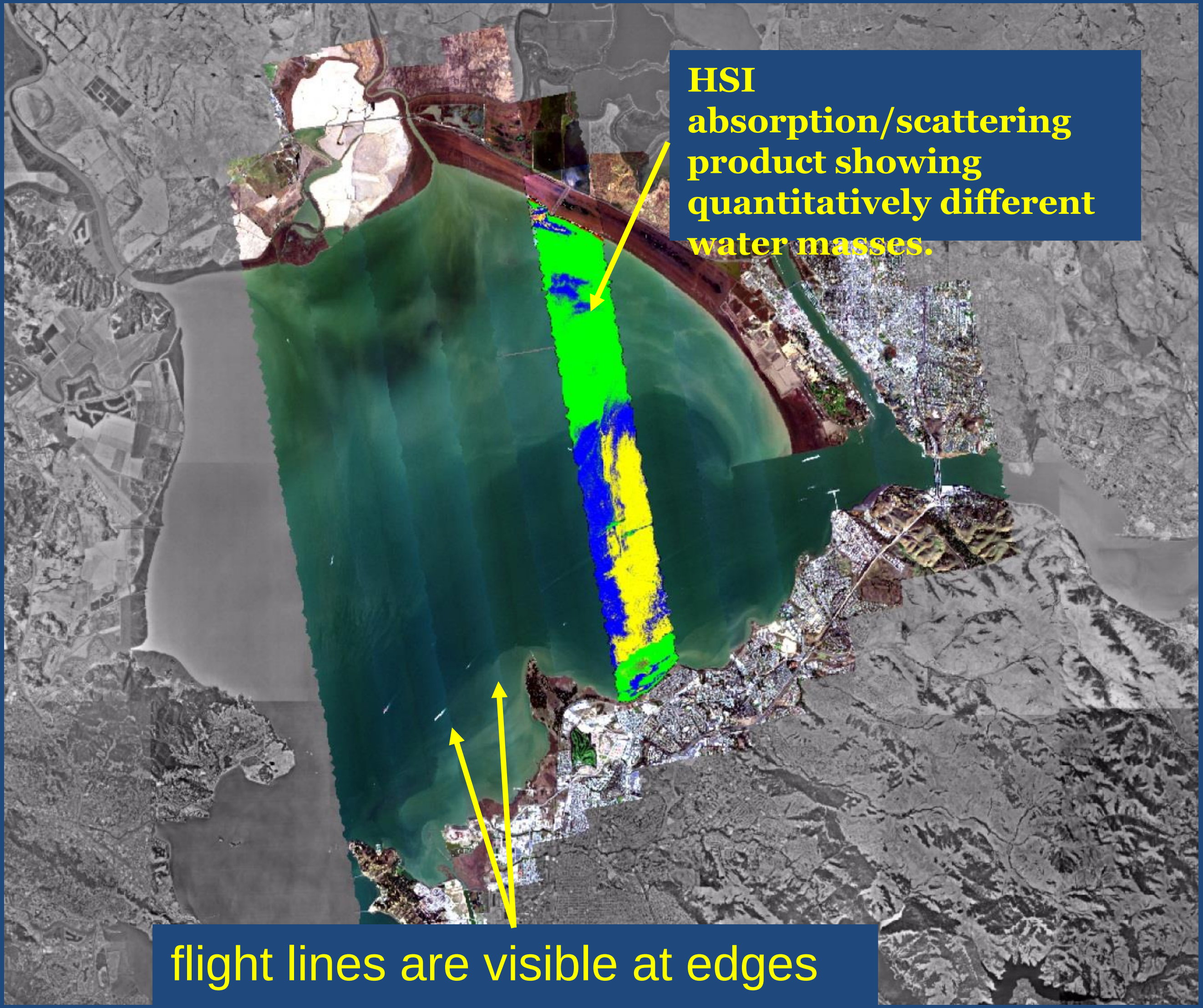


When correcting an image, each pixel in the scene has a different viewing geometry, and thus gets a different correction.

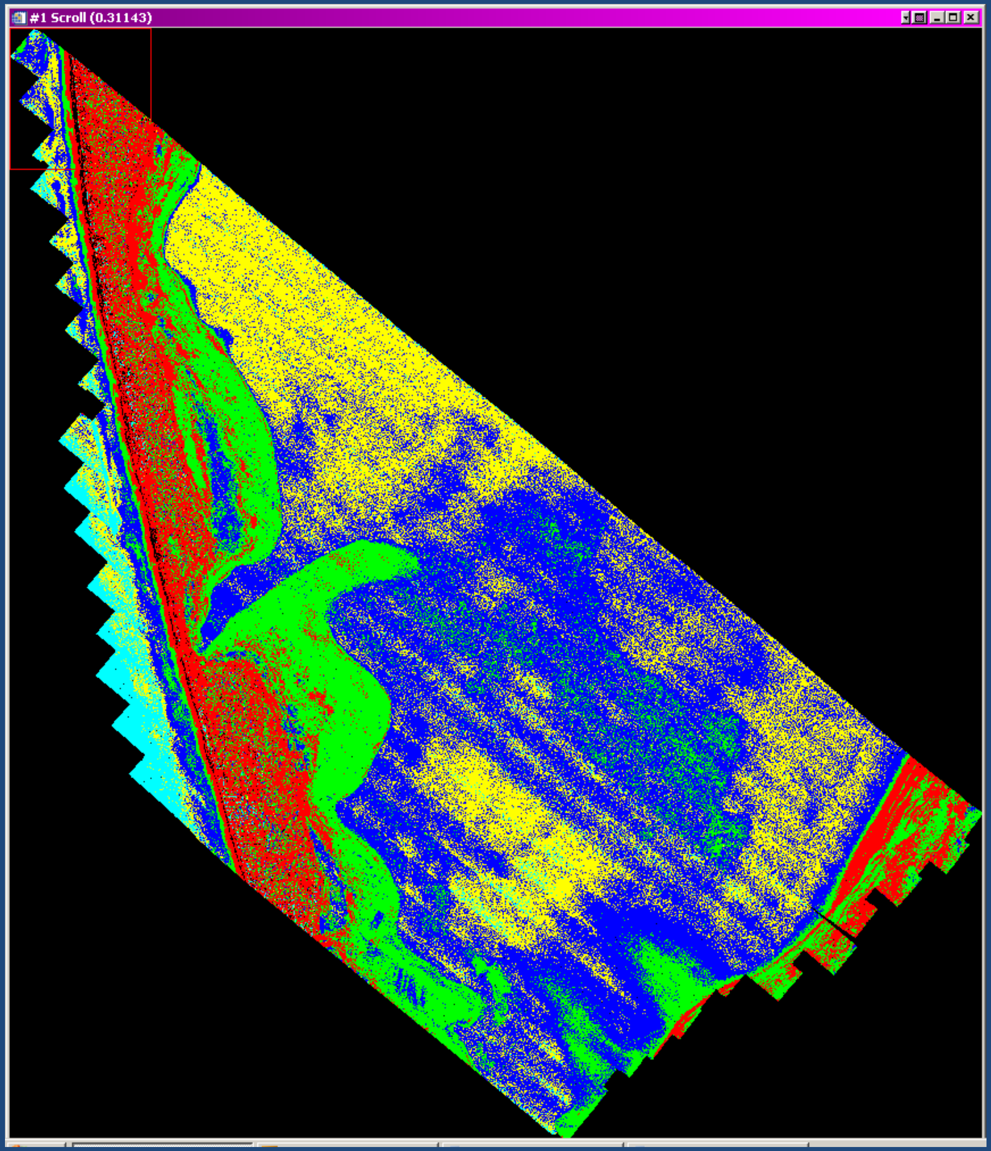
The main disadvantage of any RT method is that it requires measurement or estimation of the atmospheric properties.

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

Imperfect Atmospheric Correction Visible in RGB



Imperfect Atmospheric Correction Effects on Bathymetry



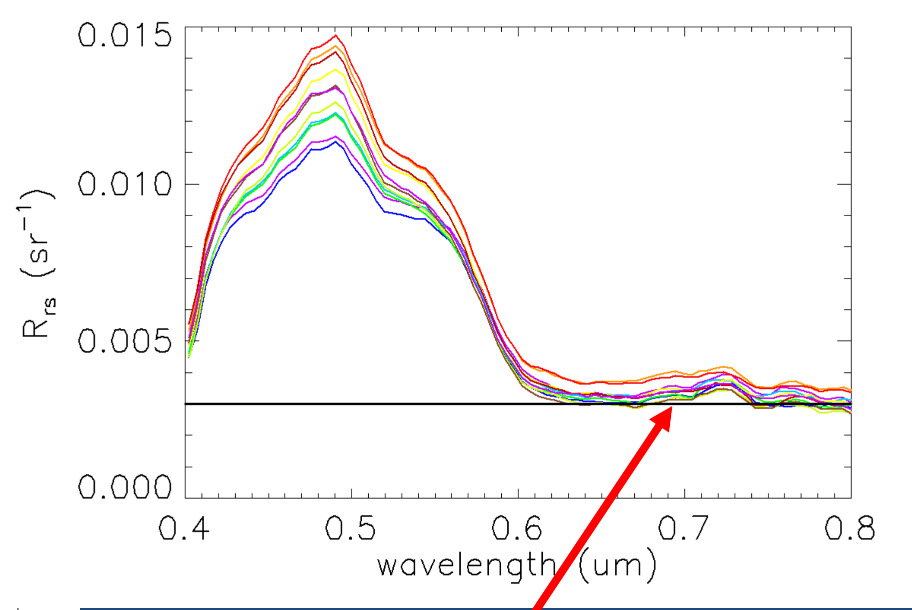
Effects of imperfect atmospheric correction on retrieved (by spectrum matching) bathymetry. The overall pattern is correct but note the “striping” in retrieved depths.

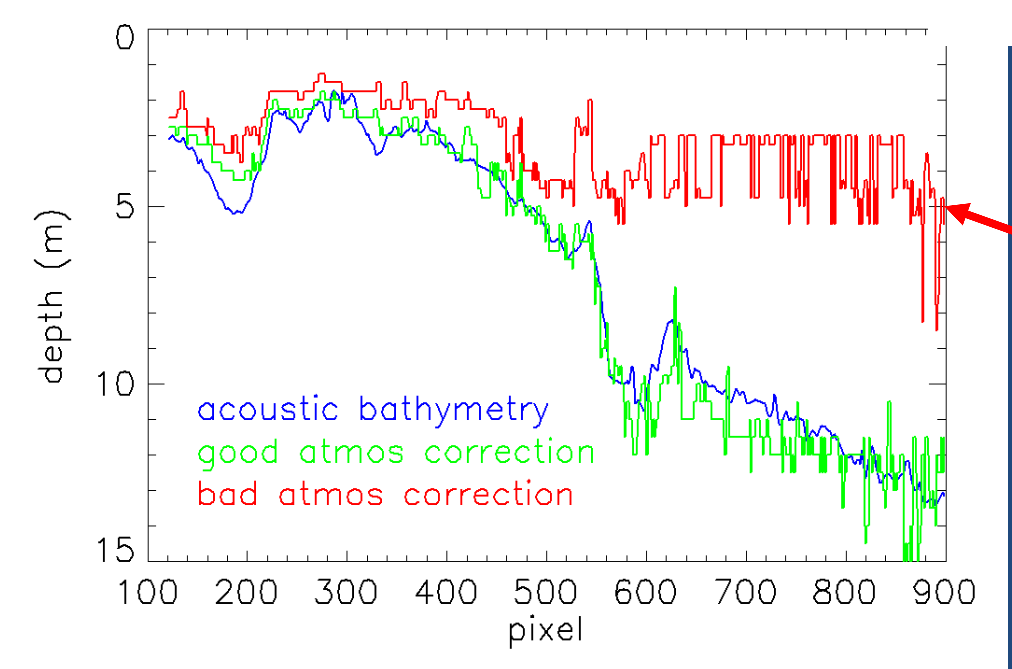
1 m contours (RGBYC =1-5 m)

courtesy of P. Bissett, FERI

Bad Atmospheric Correction = Bad Retrieval

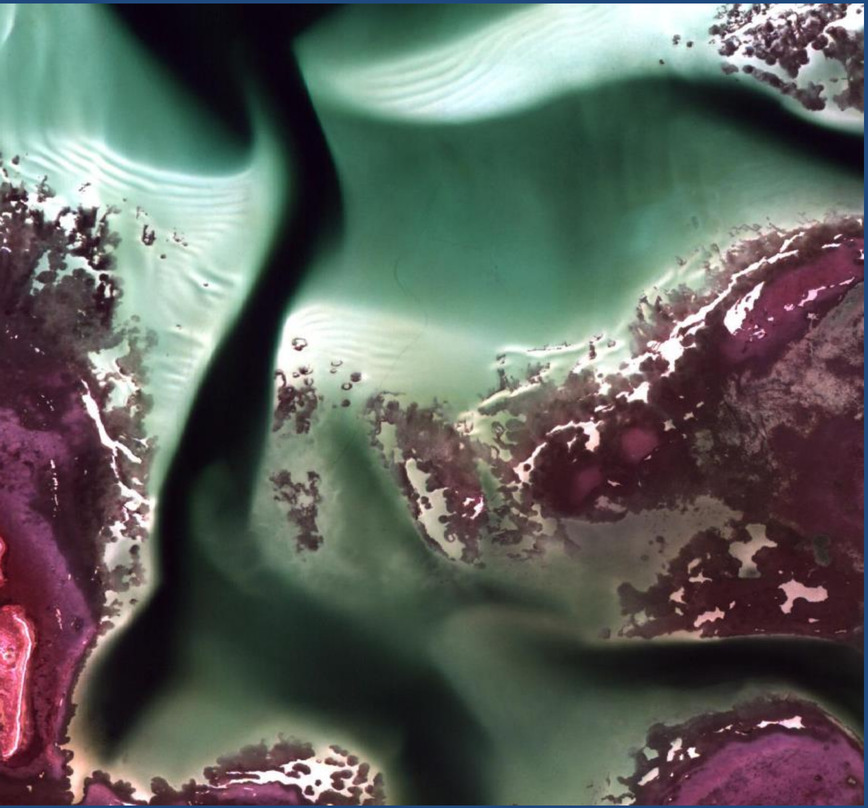
Good retrievals depend on having a good atmospheric correction



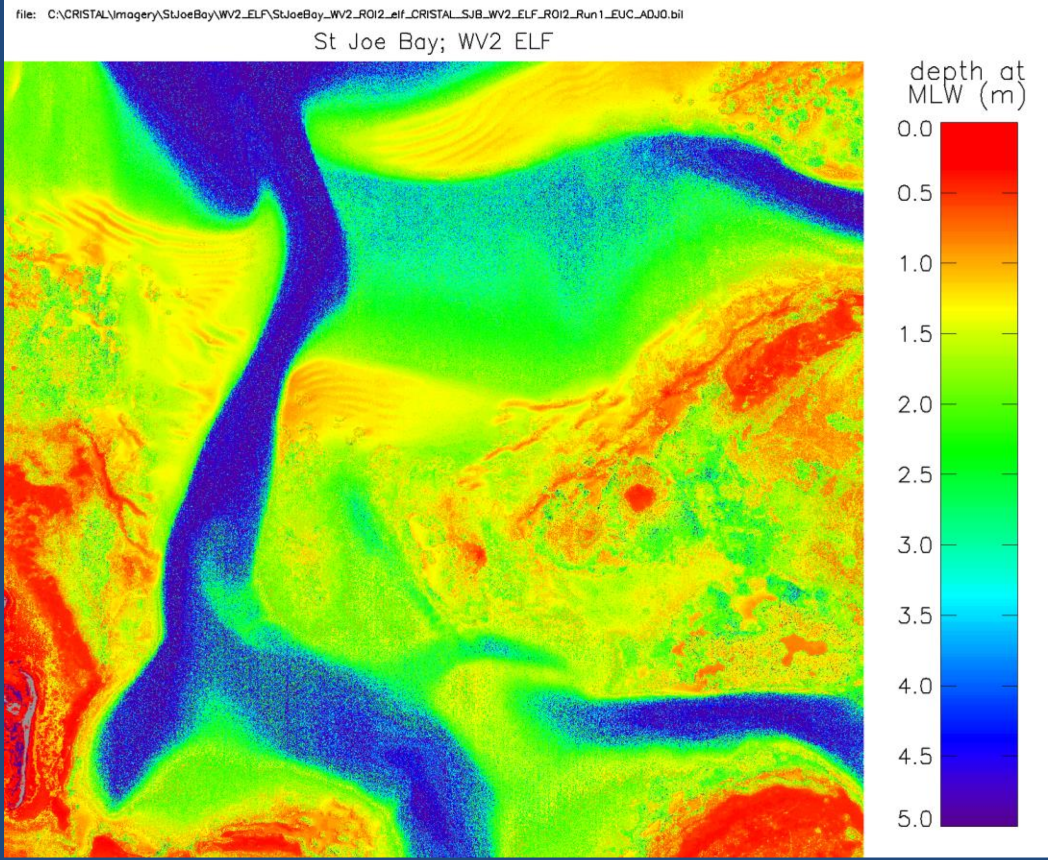


atmospheric undercorrection by 0.003 1/sr gives bottom depths too shallow

Case Study: St. Joseph Bay, FL and WorldView 2 Image; ELF vs TAFKAA-6S



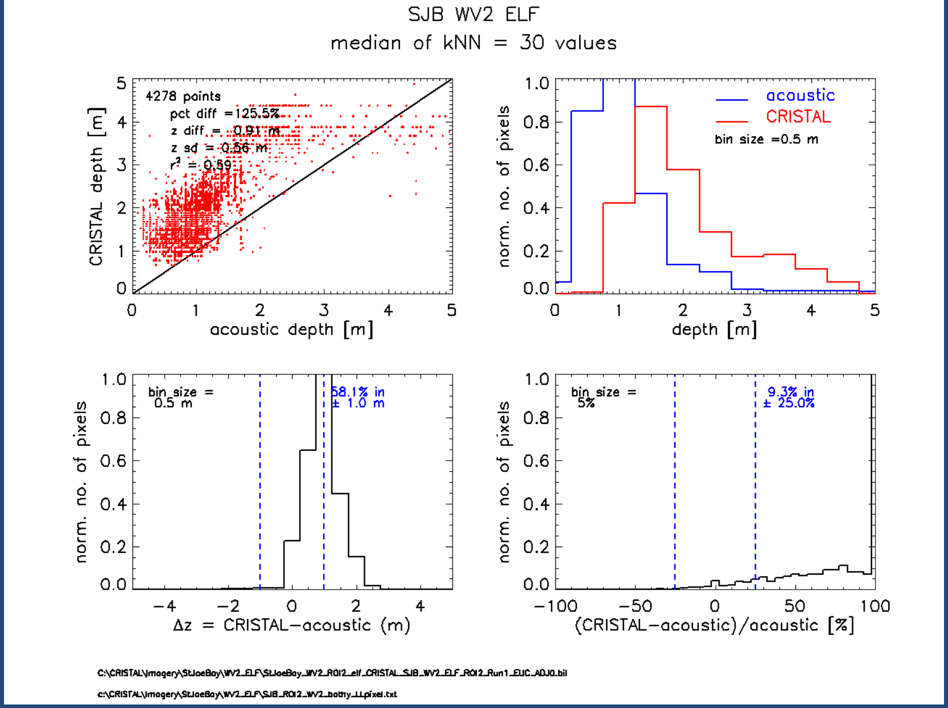
RGB of WV2 image; 2.5 x 2.5 km, ~1m GSD

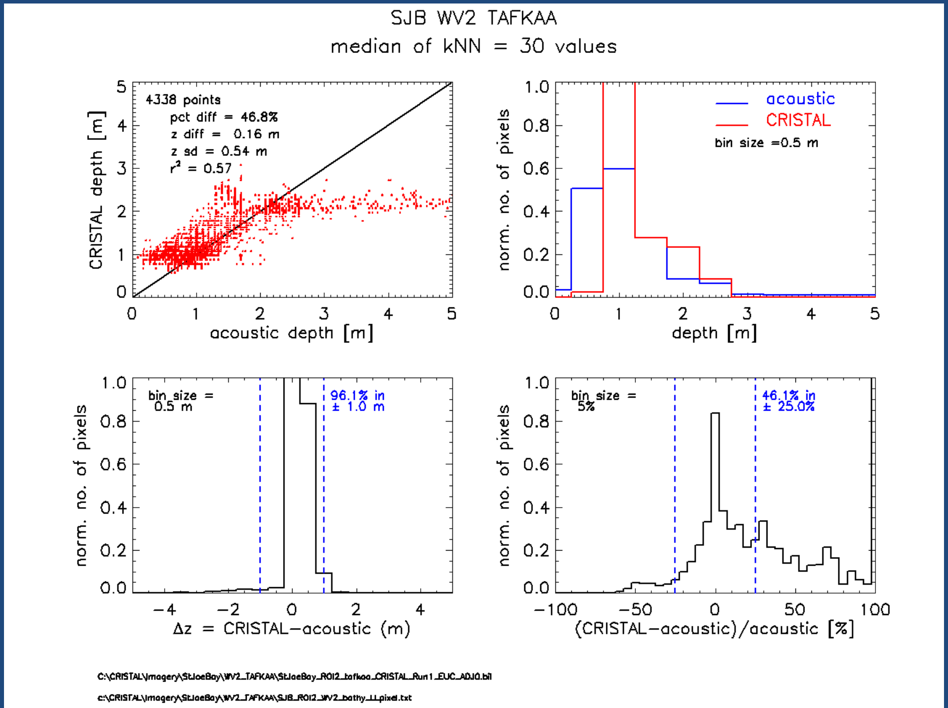


Depth retrievals are qualitatively correct

Case Study: St. Joeseph Bay, FL and WorldView 2 Image; ELF vs TAFKAA-6S

Quantitative comparison with acoustic bathymetry is not good for either the ELF or the TAFKAA corrected images. Why the poor result?



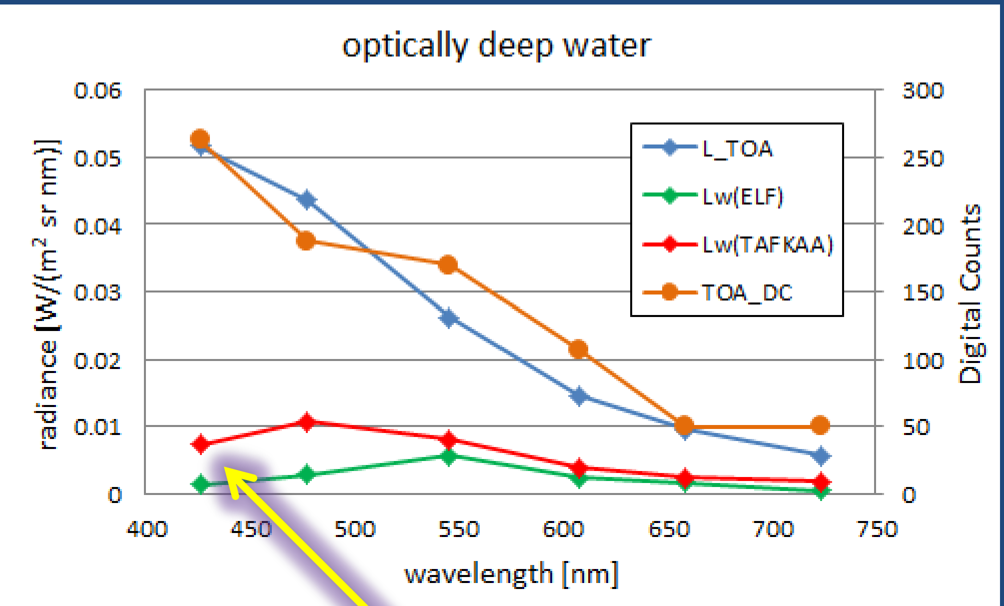


ELF-corrected image

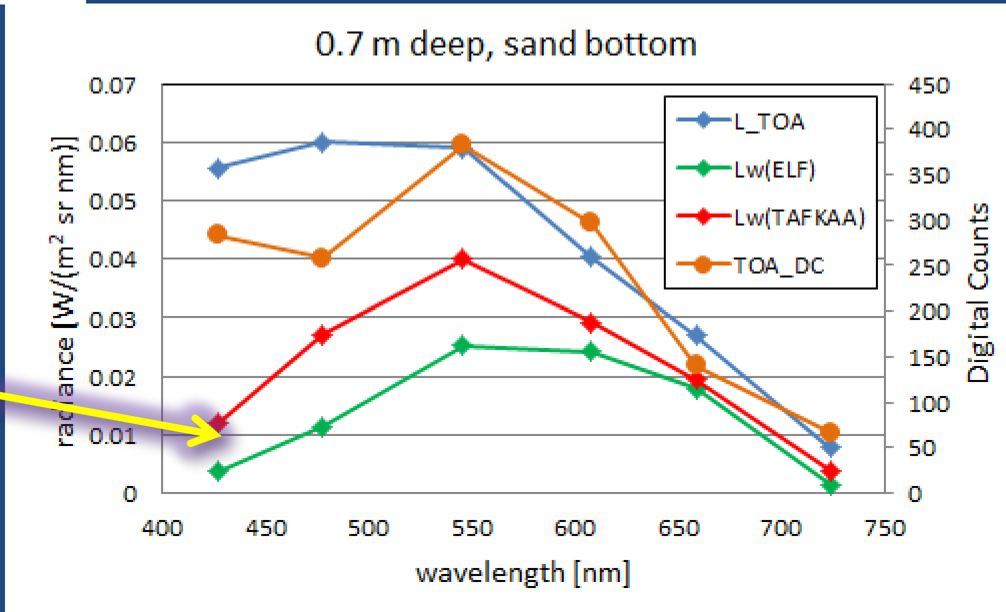
TAFKAA-corrected image

The R_{rs} spectrum-matching database was created using measured IOPs and bottom reflectances from this area, so it contains spectra representative of this environment.

The ELF and TAFKAA corrections give much different water-leaving radiance spectra.



These are HUGE differences—up to a factor of 5 at 427 nm—in ELF and TAFKAA-corrected R_{rs}



What Went Wrong?

The R_{rs} measurements used to create the EFL were made 3-8 days before the time of WV2 image acquisition.

The atmospheric conditions used as input to TAFKAA-6S were just educated guesses because no atmospheric measurements were made.

Neither atmos correction is good for this image, so the retrievals are bad.

The spectrum matching retrieval technique gave a good fit to either set of atmos corrected R_{rs}, but it was just getting a good fit to bad spectra. GIGO.

A Hybrid ELF-TAFKAA correction

Hill et al. (2014; *Estuaries and Coasts*, DOI 10.1007/s12237-013-9764-3):

- Sea-level R_{rs} measurements were made at points in the imaged area at the time of the image acquisiton (as done for ELF)
- For each R_{rs}, they searched the TAFKAA database of 75×10^6 spectra to find the one that best matched the measured R_{rs}
- The atmospheric parameters used to create the TAFKAA best-match spectrum for each measured R_{rs} were then used to deduce a single “best-guess” set of atmospheric parameters for the image area
- The deduced set of atmospheric parameters was then used (along with the sensor viewing geometry) to obtain a TAFKAA-corrected R_{rs} for each image pixel

- This worked well for their airborne hyperspectral image

Atmospheric Correction Techniques

Correlational techniques like the ELF can give good results for any atmospheric conditions.

Radiative transfer techniques such as TAFKAA can give good results for any atmospheric conditions and viewing geometry

Neither technique requires extrapolation or zero water-leaving radiances. They are therefore widely used.

The disadvantage of both is that they require measurement of R_{rs} (for ELF) or measurement or modeling of the atmospheric properties (for RT models like TAFKAA).

Both techniques will fail if you input inaccurate R_{rs} spectra or atmospheric properties. You never have all of the measurements needed, and sometimes you don't have any.

In Summary...

As we will see in the next lecture, spectrum-matching algorithms for simultaneous retrieval of ocean environmental properties (water IOPs, bottom depth, and bottom type) work well IF they have accurate R_{rs} spectra as input. Doing a good atmospheric correction on an image is the key to getting good retrievals from the image spectra.

However, atmospheric correction techniques are all imperfect, and sometimes fail completely to give useable R_{rs} spectra.

Atmospheric correction for shallow and Case 2 water is an extremely difficult problem that requires much more research, and perhaps new instrumentation (e.g., for easily and routinely measuring the atmospheric properties needed for input to RT models).

Famous atmospheric RT guru: "Curt, you'll never be able to do atmospheric correction with the accuracy you need."

Acknowledgments

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Much of this work was done in collaboration with Dr. Paul Bissett of the Florida Environmental Research Institute (FERI) and WeoGeo, Inc.

The airborne hyperspectral imagery, atmospheric corrections, and ground truth were provided by colleagues at the Naval Research Lab Code 7200 (Curtiss Davis, Valery Downes, Karen Patterson, et al.), FERI and WeoGeo, and Drs. Richard Zimmerman and Victoria Hill of Old Dominion Univ.

Everyone should go trekking in Nepal

Sunset on Machhapuchhre, 6993 m, from Annapurna South Base Camp

Annapurna I, 8091 m, from Annapurna South Base Camp

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